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THE EVOLUTION OF HERBACEOUS PLANTS AND ITS BEARING ON CERTAIN PROBLEMS OF GEOLOGY AND CLIMATOLOGY

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Evidence from living and fossil plants has often proved of value in geological investigations. A large part of our information as to the climate of the various regions of the earth during ancient times, particularly in the Mesozoic and Tertiary, has been derived from a study of the plants composing the various fossil floras with reference to the climatic conditions under which their modern representatives live. A gradual differentiation and refrigeration of climate in the north and south temperate zones since the close of the Cretaceous have been pretty clearly indicated by such investigations.[1] Botanical evidence, particularly that derived from a study of the distribution of living and fossil plants, has also been of value to the student of ancient geography in providing support for such theories as that of a closer connection between North America and eastern Asia just before the Glacial period; a recent elevation of the coastal bench in eastern North America; and a more or less intimate union between Australia, New Zealand, and South America in recent times by means of an antarctic continent or archipelago.

[1] There is, of course, ample evidence that similar periods of refrigeration have occurred earlier in the earth's history, notably in Cambrian and Permian times.

In fact, the builders of all the various hypothetical land bridges have used an abundance of phytogeographical data.

Botanical evidence which has heretofore been of use to the geologist, however, has been mainly derived from a study of *flora* rather than of *vegetation;* a study of the species, genera, and families which inhabited a region in past or present time and not of the various plant types which they represent. It is now possible, however, to supplement this evidence by an investigation of the habit of growth of the various elements in a flora, with especial reference to the relative proportions of herbs and woody plants, particularly among dicotyledonous angiosperms.[1] Data thus obtained derive their importance from the following facts which recent investigation seems pretty thoroughly to have established: (1) The earliest angiosperms were woody plants. (2) Herbs attained but very little prominence until the beginning of the Tertiary, since which time they have increased very greatly in number. (3) The gradual refrigeration of the climate of the temperate zones during the Tertiary, with the appearance of a well-marked winter season, seems to have been the factor responsible for the development of most herbs, which are plants well able to withstand cold winters, in the form of seeds or underground roots and stems. (4) This herbaceous vegetation, which reached its greatest development in the land mass of the north temperate zone, was thus composed of plants which were very hardy, agressive, and rapidly dispersed, and it consequently spread far and wide into other and warmer portions of the globe.

The evidence on which these conclusions are based may be summarized briefly as follows:

From paleobotany.—The vast majority of angiospermous remains, especially from the Cretaceous, are of plants whose nearest modern relatives are always trees or shrubs. In the Tertiary, especially the middle and latter parts of the period, remains of herbaceous plants are much more frequent. This geological evidence,

[1] The monocotyledons were apparently derived in very ancient times from the primitive dicotyledonous stock in adaptation to an aquatic habitat. They are almost entirely herbaceous, and their few woody forms are evidently recent rather than primitive.

however, cannot be regarded as entirely conclusive, since the delicate leaves of herbs are probably less readily preserved than are the tougher ones of most trees and shrubs. Among the lower orders, however, it is quite certain that the ancient fossil lepidodendrids, sigillarians, and calamites, for example, were woody plants, and that their modern representatives are all herbaceous.

From anatomy.—The most important anatomical difference between a woody plant and an herb lies in the degree of activity of the cambium. In the former group this tissue lays down a thick ring of wood which increases in size year by year. In the latter the woody ring is either very much thinner or, more frequently, is broken up into separate bundles. In such cases the so-called "interfascicular" cambium, opposite the gaps between the bundles, is much reduced or quite inactive; and in the bundles themselves the cambium is often merely vestigial. That such a discontinuous cambium is not the primitive type is shown by the fact that in various ancient groups which were just acquiring secondary growth (as shown by the structure of their fossils) the cambium always began as a perfectly continuous ring and did not arise from the union of isolated fascicular cambia.

Furthermore, in the vascular tissue of most herbs, medullary rays and wood parenchyma are poorly developed or absent. These structures, however, always characterize the more primitive types of angiosperm wood.

These two pieces of evidence point to the conclusion that the herbaceous stem has been reduced from a primitive woody one. This reduction has been accomplished by a marked decrease in the activity of the cambium, and in many instances also by an increase in the height and width of certain of the medullary rays, resulting in the breaking-up of the continuous woody ring into a series of bundles. In its general topography the stem of an herb resembles that of the young twig of its woody relatives.

From phylogeny.—It is generally admitted that the angiosperms have been derived either from the Bennettitales or from some stock derived from the Coniferales. There are no herbaceous forms in either of these groups. Among living angiosperms it is uncertain whether the nearly naked flowered Amentiferae or the complete

flowered Ranales and their allies are the most ancient members of the phylum, but the distinction in all probability belongs to one of these two groups. The Amentiferae are almost exclusively woody plants, as are the vast majority of the Ranales.

Evidence that herbaceous angiosperms are of comparatively recent origin is also presented by a study of families which possess both woody and herbaceous members and in which it is possible to determine, on floral or other evidence, the relative antiquity of the two types. In the Leguminosae, for example, the Mimosoideae and Caesalpineae are with very few exceptions trees or shrubs; and the Papilionatae, which seem clearly to be more recent than the other two groups, contain almost all the herbs in the family. In a number of other orders and families (Umbelliflorae, Violaceae, Polemoniaceae, Borraginaceae, etc.) and even in certain genera, notably *Potentilla*, the same fact may be observed. In practically every case where the phylogeny of a mixed group can be definitely established it is found that the woody members are more ancient in type than are the herbaceous ones.

Still further evidence pointing to the same conclusion is furnished by a general survey of the distribution of herbs among the families of the dicotyledons. Of the 240 families belonging to this group of plants listed in Engler's *Syllabus* (7th ed.), 121, or a trifle over 50 per cent, are entirely woody, whereas only 35, or 14 per cent, are entirely herbaceous. Eighty-four families, or 35 per cent, possess both woody and herbaceous forms. Of these 14 are rarely herbaceous and 18 rarely woody. Of the entirely herbaceous families, almost all are either parasitic, insectivorous, or water plants, or are monotypic, and hence can lay no strong claim to primitiveness. Practically all typical land herbs belong to families which have woody members, as well; but many more than half of the families possessing woody species (121 out of 205) include no herbaceous forms at all. Had the original type of angiospermous vegetation been herbaceous, it would be very improbable that over half of all the families should have lost their herbaceous members. If woody plants are primitive, however, we can easily see that herbs might have arisen in only about half of the families. These facts are especially significant

because in number of *species* herbs are fully equal to woody plants.

From phytogeography.—That the differentiation and refrigeration of climate in the temperate zones, particularly in the north temperate land mass, have been the chief factors in the development of herbs is indicated by the present distribution of these plants over the earth. In temperate regions, which are subject to winter temperatures considerably below freezing, from 75 to 85 per cent of the dicotyledonous plants are herbaceous in habit. In arctic and alpine regions, which are still colder, from 85 to 90 per cent or more of the dicotyledons are herbs. The relative proportion of the two types is precisely reversed in tropical countries and under climates where freezing never occurs. In such regions only from 25 (or less) to 40 per cent of the dicotyledons are herbs. Table I presents an analysis of the dicotyledonous vegetation in several typical temperate, arctic, alpine, and tropical regions.[1]

TABLE I

Region	Number of Species	Number of Herbs	Percentage of Herbs
Northeastern United States	2,280	1,748	76
Rocky Mountains	2,206	1,910	86
Ellesmereland	76	71	93
Great Britain	927	821	88
Germany	1,117	947	84
Switzerland	1,899	1,726	90
Iceland	221	200	90
Brazil	15,981	4,092	25
British West Indies	2,249	675	30
Tropical Africa	8,577	3,560	41
Java	3,188	867	27

This evident adaptation of herbs to life in regions subject to low temperatures at certain seasons makes it very probable that the advent of a cold winter has indeed been the chief factor responsible for their origin, for there is a fairly constant relation between the minimum winter temperature of a region and the proportion of

[1] In all of the tropical regions of which the floras are tabulated here, there are more or less extensive upland or mountain areas which possess a relatively temperate climate and hence a fairly high proportion of herbs. In the tropical lowlands in each case, however, only from 10 to 15 per cent of the dicotyledons are typically herbaceous.

woody plants in its flora. The advantages of the herbaceous habit in a temperate climate are obvious. The plant is able to complete its whole life-cycle during the summer season and to live through the cold winter either under ground or in the form of seeds. Plants which cannot resist cold are thus able to thrive in temperate regions. It is a noteworthy fact that families whose members have aerial stems which are generally able to withstand low temperatures—such as the Fagaceae, Betulaceae, Salicaceae, Caprifoliaceae, and, in fact, most of the woody families of temperate regions—have few or no herbaceous species, for they have been well able to get along without them.

The gradual refrigeration of climate probably first dwarfed and stunted the primitive arborescent vegetation, killing outright many of the more delicate types, such as the fig, laurel, and cinnamon (of which we find fossil remains almost within the arctic circle); and then, by continually killing back the whole year's growth of these stunted shrubs, it probably converted them gradually into perennial herbs. The annual herb, which starts from seed each year, is evidently a still more recent development.

The herbaceous type thus developed has usually proved very vigorous and adaptable. It is far superior to the woody one in the relative amount of seed which it produces; and the fact that its life-cycle from seed to seed is completed in only one or two seasons, rather than in the long period of years which is necessary with most trees and shrubs, allows it to become dispersed much more rapidly. Its ability to live through adverse conditions of drought, in the same way that it does through those of cold, gives it an advantage in dry regions, and many herbs seem to have arisen in these dry regions in adaptation to discontinuity in moisture alone.

It seems most probable that herbs have evolved in the temperate portions of the Southern Hemisphere and in mountainous, desert, and even tropical habitats all over the world. The majority of the important herbaceous genera, however, seem from their present distribution to have originated in the temperate land mass of the Northern Hemisphere. The ease of dispersal over wide areas and the consequently keen competition among a great variety of plants have resulted here in the development of an exceedingly hardy and

aggressive herbaceous flora. Most of the dominant and widely spreading plants of today, including practically all weeds, originally belonged to this northern herbaceous vegetation. These "Scandinavian" plants have taken advantage of every opportunity to become widely dispersed and to establish themselves in other parts of the world, with the result that in the temperate regions of the Southern Hemisphere, for example, there are well over two hundred genera and even fifty or more species which are identical with northern ones; and in practically all the south temperate floras more than half of the herbaceous genera either have their center of distribution in the Northern Hemisphere or are very common there. There are comparatively few southern genera, on the contrary, which have successfully invaded the North.

That the evolution of herbs has taken place for the most part since the close of the Mesozoic is indicated not alone by the fact that refrigeration of climate seems to date from that time but also from the following phytogeographical evidence. In the four great temperate land masses of the Southern Hemisphere (Australia, New Zealand, temperate South America, and South Africa) the endemic genera and the very characteristic families, which undoubtedly represent the most ancient element in the vegetation, are com-

TABLE II

	Total	Herbs	Percentage Herbs
Australia—			
Species of non-endemic genera	2,301	1,251	54
Species of endemic genera	4,024	677	17
New Zealand—			
Species of non-endemic genera	711	460	64
Species of endemic genera	315	109	34
Patagonia—			
Species of non-endemic genera	920	720	76
Species of endemic genera	667	320	48
South Africa—			
Species of non-endemic genera	3,298	1,929	55
Species of endemic genera	4,686	1,390	29

posed, in very large majority, of woody plants,[1] as shown in Table II. Most of the indigenous herbs, however, belong to genera, and often

[1] "Endemic" genera are those which are either strictly confined to the region in question or have only a very few species outside of it.

even to species, which are identical with those in northern latitudes, and are therefore in all probability recent immigrants.

The slight degree of endemism among these southern herbs is the more significant when we remember that such plants, from the brevity of their life-cycle, are likely to change much more rapidly than woody forms and hence would develop into endemic types in a shorter time. The notable uniformity of flora, too, over most of the globe during the Cretaceous, as shown by fossil evidence, renders it very improbable that, if herbs had been a dominant feature of the vegetation of that period, they would now be so uniformly absent from the ancient portion of the southern floras. The union of southern Africa with Eurasia in the Miocene and the union of South America with North America in the Pliocene evidently mark the periods of the herbaceous invasion of these two continents. Australia has apparently been sufficiently isolated from Asia since the Cretaceous so that land animals have been unable to enter it. The northern members of its flora, however, have doubtless effected their entrance by a migration, in comparatively recent times, over the Himalayas and along the East Indies. Had herbs been numerous in the latter part of the Mesozoic, when the connection of Australia with Eurasia was evidently much more intimate, the present vegetation of the island continent would certainly contain a much higher percentage of such plants. That the very early Tertiary flora of Australia included few if any herbs is made even more certain by the fact that although in all probability northern Australia and New Zealand were connected at that period by a land bridge, none of the northern herbs which entered Australia from the East Indies are now found in New Zealand; and we are obliged to infer that they had not then arrived in Australia.

The period at which herbs became an important feature of the north temperate vegetation and began to spread thence southward is therefore pretty clearly set at somewhere in the early Tertiary.[1] That herbaceous dicotyledons existed in the latter part of the Mesozoic, however, especially in mountainous regions, is most

[1] Recently discovered evidences of glaciation just at the close of the Cretaceous are of importance in this connection.

probable, but it seems equally probable that their great development did not take place until after the close of that epoch.

Such, in brief, is the evidence for believing that herbaceous angiosperms are comparatively recent in origin; that they have been developed most abundantly in the north temperate zone, mainly since the Cretaceous, as an adaptation to the advent of a winter season; and that they have spread thence over most of the other regions of the earth. Let us now see what conclusions of importance to geologists and climatologists may be drawn from a study of the origin and dispersal of these herbs.

In the first place the distribution of herbs in the north temperate zone provides us with evidence as to the climate of this area at the time of the last Glacial epoch.

As to what was the composition of the northern flora before the advance of the ice sheet we cannot be very certain, but there is reason to believe that a much higher proportion of woody plants flourished there than at present, indicating the existence of a climate devoid of extreme cold. Such an inference is based on the composition of that considerable body of related species and genera which are common to eastern North America and eastern Asia and which are nearly or quite absent elsewhere. Gray[1] was the first to suggest that these plants were the remnant of the widespread pre-Glacial boreal flora which had been forced south by the advance of the ice and had been exterminated almost everywhere save in these two regions, which were the only ones in warmer latitudes into which it had been able to escape. If this hypothesis is correct, as subsequent investigations seem to indicate, and if this group of plants is truly a fair sample of the pre-Glacial flora of the north, a study of its composition is of considerable interest. Gray has published a list of the genera and species of eastern North America which are absent in Europe but which are represented by identical or closely related forms in eastern Asia. This list comprises 142 genera of dicotyledons, of which 70 are woody or predominantly so, and 240 species, of which 128 are woody. The flora is thus just about equally divided between herbs and woody plants. From the greater hardiness of most herbs it is probable that they have

[1] A. Gray, *Scientific Papers* (1879).

suffered less by extinction than have the woody plants, and consequently that even more than 50 per cent of the original boreal dicotyledonous flora consisted of woody forms. This analysis would seem to indicate that previous to the glacial invasion the climate of the north temperate zone had, for a long time at least, been devoid of extremes of cold. We know from fossil evidence that in several regions during the Tertiary temperate genera, such as oaks and poplars, grew side by side with such tropical or subtropical types as the palm and fig; and it therefore seems reasonable to infer that the climate was a very equable one and devoid of extremes of heat as well as of cold.

More conclusive evidence, however, is at hand as to climatic conditions near the ice front during the actual period of the glacial invasion. The vegetation of the whole temperate zone at that time of course lost heavily by extermination, but this extermination must have been much more pronounced among woody plants than among herbs, owing to the greater ability of the latter to withstand cold and other adverse conditions. It is a significant fact that the present flora of Europe north of the Alps is decidedly more impoverished than is that of corresponding temperate North America, and that although in the latter region approximately 25 per cent of the dicotyledons are woody, in the former only from 10 to 15 per cent are so. This paucity of indigenous trees and shrubs in northern Europe is especially noteworthy since experiment has shown that many species of delicate and warmth-loving trees and shrubs will grow in England, France, and Germany which cannot stand the droughts and winters of the northern United States. In America, too, there are representatives of a considerable number of woody families which are now absent in northern Europe, many of which occur there as fossils. These facts are evidently to be explained by the much greater adversities suffered by the European flora during the Glacial epoch. In North America, especially in its eastern portion, the vegetation could easily migrate southward at the advance of the ice and return northward at its retreat. In northern Europe, on the other hand, the southward escape of the vegetation was blocked, and it was crowded against the Alps, the Pyrenees, and the Mediterranean, thus suffering

heavily by extinction. These same natural barriers have also prevented any considerable northward migration since the retreat of the ice. The vegetation of northern Europe today seems, therefore, to be descended directly from that remnant which was able to survive on the unglaciated portions of France, Germany, and England. We have already noted the fact that the percentage of woody plants in the dicotyledonous flora of northern Europe is amazingly low, being only from 10 to 15 per cent of the whole. This is really a percentage typical of alpine or northern regions. Indeed, the proportion of herbs in Switzerland today is but little higher than that in the adjacent lowlands. The alpine character of the northern European flora is further emphasized by the strong resemblance which it bears to that of the flora of the Rocky Mountains, for the two floras are composed of almost exactly the same families and include a host of identical genera and even a large number of identical species. In fact, the flora of the Rockies presents a much closer resemblance to that of Europe than does the flora of the eastern part of the continent.

If the flora of northern Europe is indeed typically representative of that which flourished near the ice front during glacial times, the proportion of woody forms within it affords us a valuable index as to climatic conditions during the height of the ice age. The facts seem to indicate that when the ice sheeet had reached its greatest extent the country in its immediate front was neither a barren arctic tundra, as has sometimes been supposed, nor covered with a luxuriant temperate vegetation; but that the climate in general resembled that of the lower portions of the Alps or the Rockies today, being cold enough in winter to kill off all but the hardiest trees and shrubs but not sufficiently cold to reduce the whole vegetation to the few perennial herbs and stunted shrubs which are characteristic of arctic regions today. Of course this evidence is of value only as indicating the climate during the *coldest* period of the ice invasion, just as the percentage of herbs in a flora is indicative of the minimum winter temperature of the region. As to the climate of the presumably warmer interglacial periods it tells us nothing.

This conception of the dicotyledonous herb as a comparatively recent type of plant which has been developed extensively in the north temperate zone during the Tertiary and has spread thence far and wide over the globe also leads us to some interesting geographical conclusions. Those regions, such as southern Asia and Mexico, which have been invaded, at least in their more temperate portions, by a flood of northern herbs, have in all probability had a nearly or quite continuous land connection with northern Eurasia or North America during Tertiary time. Other regions, such as Australia, New Zealand, South America, and South Africa, where there is a markedly smaller percentage of herbs in the vegetation, have apparently had a much less intimate connection with the great land mass of the north temperate zone during the Tertiary. This is particularly true of certain oceanic islands, notably Hawaii, the Polynesian group, Juan Fernandez, the Canaries, St. Helena, Socotra, Mauritius, and the Seychelles, on which the percentage of herbs is much smaller than on the adjacent mainland. In these insular floras practically all the herbs belong to species which also occur on the near-by continent; and almost the entire body of the endemic genera, presumably the most ancient portion of the flora, is composed of woody plants, as is shown in Table III.

TABLE III

	Total	Herbs	Percentage Herbs
Hawaii—			
Species of non-endemic genera	339	117	34
Species of endemic genera	243	21	8.6
Fiji—			
Species of non-endemic genera	543	81	15
Species of endemic genera	20	0	0
Juan Fernandez—			
Species of non-endemic genera	57	27	47
Species of endemic genera	17	0	0
St. Helena—			
Species of non-endemic genera	34	15	44
Species of endemic genera	7	0	0
Mauritius and the Seychelles—			
Species of non-endemic genera	524	191	36
Species of endemic genera	63	3	4.7

This paucity of herbs, particularly of annuals, on oceanic islands was noted long ago by Darwin, Hooker, and others, and was ex-

plained (by Darwin[1]) as due to the fact that the lessened competition between the members of an insular flora allowed many plants to grow there into shrubs and trees which on the mainland could never succeed in attaining more than a herbaceous stature. From what we have seen as to the evolution of herbs this explanation appears inadequate, and it implies that, in many cases, herbs must have lost their great advantage of being able to pass from seed to seed in a single season. Insular floras appear rather to be relics of the ancient Tertiary vegetation which once flourished on the adjacent mainlands but which has been more or less superseded there by an influx of new plants, most of them herbs. The many striking differences in flora between Juan Fernandez and adjacent Chile; the Canaries and adjacent Morocco; St. Helena and adjacent South Africa; and Socotra and adjacent Somaliland seem to point to this conclusion. Strongly in favor of such a view are also the very numerous floral resemblances exhibited between distant islands or between islands and distant continents. The occurrences of shrubby species of Plantago only in Hawaii, Juan Fernandez, and St. Helena; of phyllodineous Acacias only in the Mascarene region, Hawaii, and Australia; of related shrubby Compositae in Hawaii, Tahiti, the Galapagos, and Juan Fernandez, and of numerous related species in the Canaries, South Africa, and Socotra constitute a few of many instances of such distribution. The very large proportion of woody plants compared to herbaceous plants in these insular floras and the high degree of endemism of the former as opposed to the latter strongly favor the theory that these particular islands do indeed support a very ancient type of organic life, and that since the opening of the Tertiary at least they have not been intimately connected with any large continental area.

Other isolated islands or archipelagoes, such as Bermuda and the Azores, possess as high a percentage of herbaceous plants in their vegetation as do the adjacent continental areas, and they likewise have a very small endemic element. We are forced to conclude, on evidence both from the flora and from the composition of the vegetation, that such islands have appeared, or at least have received their plant life, in comparatively recent times.

[1] C. Darwin, *Origin of Species*, 6th ed., p. 413.

Aside from its bearing on the antiquity of oceanic islands and other isolated regions, the present theory as to the origin and dispersal of herbs is of importance as indicating the conditions under which occurred that momentous botanical event of the Tertiary—the invasion of the Southern Hemisphere by a flood of northern plants. Phytogeography indicates that this invasion took place along three main routes: over the Andes into Patagonia and thence over an extensive antarctic continent or archipelago into New Zealand and southeastern Australia; over the central African highlands into South Africa and Madagascar; and over the Himalayas and along the East Indies into Australia. These invasions seem to have ceased entirely at the present time, for there are in most cases wide gaps of hundred or even thousands of miles between the northern and the southern ranges of a genus or a species. That the immigration into Africa and Asia ceased some time ago is indicated by the fact that in these continents there are now almost no species identical with northern ones, although the genera are still the same. The highway over the Andes, however, seems to have closed much more recently, for there are a large number of species which traversed it that are still identical with their boreal types. The significant facts in this connection are that, with the exception of a very few genera which are poor in species, this invasion by the "Scandinavian" flora was an invasion of *herbs*,[1] and that herbs are peculiarly adapted to temperate climates. This immediately suggests the conclusion either that these three mountain highways were considerably more elevated during the Tertiary, with a consequent increase in the extent of temperate areas (a

[1] The presence of such temperate types as Betula, Populus, and Quercus in the Cretaceous of Patagonia, as described by F. Kurtz ("Contribuciones a la palaeophytologia Argentina—Sobre la existencia de una Dakota flora en la Patagonia austro-occidental," *Revista museo la plata*, X [1899], 1902, pp. 43–60), and in the Cretaceous and even Tertiary of Australia and New Zealand by Baron C. von Ettinghausen ("Tertiary Flora of Australia," *Gov. Surv. N.S.W. 1888*, p. 82; "Contributions to the Knowledge of the Fossil Flora of New Zealand," *Trans. New Zealand Inst.*, XXIII [1890], 237) (the latter's identifications are often open to grave question, however) has probably nothing to do with the Tertiary invasion of herbs but rather bears witness to the remarkable uniformity and intermingling of the Cretaceous flora. Had these ancient temperate plants been accompanied by anything like the throng of herbs which now surrounds them in the north, it is highly improbable that herbaceous forms would now be so scarce in the south temperate zone. Because of the brevity of their life-cycle, herbs are likely to change very rapidly, and the slight degree in which these "northern" herbs in the antipodes have become altered also bears witness to their comparatively recent arrival.

hypothesis which the Tertiary origin of the Andes and Himalayas may perhaps be regarded as supporting); or that for some other reason, possibly an increase in glaciation, the area of regions enjoying a cool climate in the tropics has at various times been considerably augmented.

In this connection it is of interest to note the evidence which is accumulating as to the occurrence of more or less widespread glaciation both at the transition from Cretaceous to Tertiary and again during the Miocene. It is possible that the more ancient herbaceous invasions were coincident with these earlier glacial periods and that the later migration of such plants into the antipodes was contemporaneous with the extensive glaciation which marked the latter part of the Tertiary.

The theory put forward by Hackel[1] and supported by Scharff[2] asserts that the boreal plants in antipodean South America are extremely ancient types which have preserved their specific identity for an exceedingly long time; that they migrated over a land bridge long since destroyed; and that instead of having come south along the Andes they are at present going north. Such a theory is certainly not tenable if herbs are proven to be of recent origin. The increasing frequency of northern herbs as one goes south along the Andes, the fact on which Hackel's hypothesis is based, is well explained by a decrease in temperate areas within the tropics as by a migration from the south. It is also very difficult to imagine so many forms maintaining or almost maintaining their specific identity for such a very long period of time. The present theory of the origin of herbs certainly supports the view that they have entered the antipodes rather recently over land bridges which have not had time to become fundamentally altered.

We have already spoken of the antarctic continent as a highway between South America and Australasia; and the existence in comparatively recent times of such an extended Antarctica, able to support a large fauna and flora, has been postulated by almost all students of the distribution of antipodean plants and animals.

[1] E. Hackel, "Über die Beziehungen der Flora der Magellansländer zu jener d. nördl. Europa und Amerika," *Mitteil. naturw. Verein Steiermark* (Botan. Sekt.) (1905), pp. 110–15.

[2] R. F. Scharff, *Distribution and Origin of Life in America* (1912), p. 418.

That during its greatest extent, however, it was probably not a continuous land bridge but more in the nature of a great archipelago, presenting a barrier to most animal invaders but much more easily crossed by plants, seems to be generally admitted. It is worth our while to analyze the ancient "endemic" flora of this antarctic continent and archipelago and to find, if we may, what the climatic conditions were under which it flourished. It seems to be a reasonably safe conclusion that all genera commonly designated as "antarctic," from their confinement to the temperate regions of the Southern Hemisphere, were once inhabitants of Antarctica. The writers have compiled a list of eighty-eight dicotyledonous genera which have representatives in at least two of the three main antarctic regions—New Zealand, Australia, and temperate South America—and which possess but very few species outside these regions. This list may well be regarded as representative of the flora of Antarctica (except for the northern invaders) before the advent of the cold period which drove the phanerogamic vegetation northward into South America and Australasia. Of these eighty-eight genera only thirty-four, or 38 per cent, are typically herbaceous. These few herbs are obviously unrelated to northern ones and seem clearly to have had an independent origin in the antipodes in response to the refrigeration of the climate. That they are not as ancient as the northern herbs appears to be indicated by the fact that the annual type has not yet been evolved among them. If the northern invasion which crossed Antarctica did not enter it until the Pliocene (as seems probable), no very extreme refrigeration could have taken place until the latter part of that period, at any rate. The very high percentage of woody plants in the original flora, however, seems to testify strongly to the existence in Antarctica at no very ancient date of a climate devoid of extreme cold. The refrigeration of this climate and the evolution of its herbaceous vegetation, instead of being the slow and gradual processes that they were in the Northern Hemisphere, seem to have been much more rapid. The consequently scanty number of herbs and the lack of time or space for very vigorous competition among them doubtless explain why the antarctic herbs are not as widespread and aggressive as their northern congeners.

Such are the more important geological and climatological inferences to which we are led by a recognition of the recent and predominantly boreal origin of herbs, and of the factors which have determined their origin. Much more complete data must be sedulously gathered, particularly by the phytogeographer and the botanical phylogenist, before the full application of this theory to the problems of geology can be definitely determined. That it is possible, however, to draw conclusions of importance to geology and climatology, not alone from the past and present distribution of species, but also from a study of the evolution of the growth of habits of plants, will be readily admitted.[1]

SUMMARY

1. The earliest angiosperms were woody plants, and herbs have been derived from them by reduction. This is indicated by the facts that: (1) the earliest angiosperm fossil remains are almost entirely of woody plants; (2) the uninterrupted and active cambial ring of woody dicotyledons, which lays down secondary wood provided with well-developed medullary rays and wood parenchyma, is the primitive type and that the much reduced secondary tissues in herbs are clearly derived from this; (3) the ancestors of the angiosperms and the great majority of the primitive members of the phylum are woody plants; and that (4) in all families and genera which contain both woody plants and herbs the latter are more primitive in their constitution.

2. The differentiation and refrigeration of the climate of the temperate zones since the beginning of the Tertiary, and the consequent appearance of a cold winter season, have been the chief factors which have caused the evolution of herbs. Herbs are able to survive adverse conditions of temperature or moisture as underground roots and stems or in the form of seeds, and can thus thrive in regions where plants with perennial aerial stems would perish. In general, the lower the winter temperature of a region the fewer the woody plants in its flora.

3. At least half of the pre-Glacial vegetation of the north temperate zone seems to have been composed of woody plants,

[1] A more complete discussion of the present problem with the presentation of a much larger body of data will be found in a paper by the writers, "The Origin and Dispersal of Herbaceous Angiosperms," *Annals of Botany*, XXVIII (1914), 547–99.

indicating the occurrence of a rather mild winter. The advent of the Glacial period resulted in very great extermination of the flora, but herbs suffered much less than did woody plants.

4. In America the vegetation was able to return northward after the retreat of the ice and thus shows a considerable proportion of woody species today. In northern Europe, however, natural barriers have to a great extent prevented this return, and the present flora of that region seems to be descended from the remnant of the pre-Glacial vegetation which survived on the unglaciated areas. The fact that the proportion of herbs in the present north European flora is like that in northern or low alpine regions today provides us with a clue as to climatic conditions during the height of the glacial invasion.

5. The land mass of the north temperate zone has been the seat of origin of a very large part, if not of the majority, of herbaceous genera. The opportunities for wide dispersal and keen competition here have resulted in the production of a very hardy and aggressive herbaceous flora which has spread widely into the tropics and the Southern Hemisphere.

6. This invasion of herbs from the north has taken place for the most part during the Tertiary, and the percentage of herbs in the floras of the various regions in the tropics and the Southern Hemisphere indicates roughly the intimacy of the connection between these regions and the land mass of the north temperate zone during Tertiary time. The floras of certain oceanic islands, for example, seem from the extreme paucity of herbs to be very ancient in type, implying a very long period of isolation; whereas the floras of other islands, overwhelmingly herbaceous, indicate a recent origin for these islands or at least for their plant populations.

7. Boreal herbs in the antipodes are usually separated from their northern congeners by considerable distances, indicating that migration has ceased and that the wide area of rather temperate climate within the tropics, under which the invasion took place, has recently become much smaller.

8. A reconstruction and analysis of the ancient flora of the antarctic continent indicate that up to comparatively recent times its climate was very mild and that refrigeration took place more rapidly than in the north temperate zone.

POST-CRETACEOUS HISTORY OF THE MOUNTAINS OF CENTRAL WESTERN WYOMING

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PART III

Quaternary cycles of stream erosion.—Although in the higher mountains stream erosion was superseded at intervals by glaciation, over most of the district the Quaternary period was a time of continuous action by running water and its accessory agencies. The erosion history was accented, however, by several changes which rejuvenated the streams from time to time, and thus prevented the completion of the successive erosion cycles. Conceivable causes of such interruptions are: (*a*) a series of general uplifts; (*b*) the readjustment of stream grades on account of the removal of obstructions in the channels of the master rivers, or because of piracy in their lower courses; and (*c*) notable changes of climate.

Of these causative changes, those which were climatic should have produced more or less harmonious results simultaneously over the entire district. The same should have been true of the gentle elevatory movements, if they were uniform over wide areas. The two factors should differ in their results in that climatic changes would doubtless make themselves felt all over the district at the same time, and streams would then respond either by trenching their floodplains or by aggrading them. The changes would apparently take place simultaneously throughout the entire graded profiles of all the streams. The elevatory movements, however, if equal everywhere, would cause rejuvenation first in the lower courses of the streams, or, in this instance, outside the district. The phenomena due to elevation or depression would then migrate up the individual streams; in such cases the new cycle features of the lower courses would be distinctly older than those of the upper courses at any given time. If the surface of the district, instead of

being uniformly raised (relatively), was warped, then the readjustments of stream action and their results must have been more complex. Rejuvenation due to the removal of falls and rapids or to stream-piracy would be likely to cause changes in one valley system which would have no counterpart in the adjacent drainage basins.

Climatic change may well explain some of the minor rejuvenations, but apparently is incompetent to account for the cutting of valleys hundreds or even thousands of feet deep. Inasmuch as it is not only possible, but fairly probable, that several or even all of these changes have been at work, it is clear that the problem to be dealt with is by no means simple; it should be approached in a spirit of caution and without an expectation of solving it completely except after more detailed field studies. It is an observed fact that the topographic features in different parts of the district here considered, and even in entirely different drainage basins, are so similar in aspect, in order, and in relations as to suggest that each has passed through a similar history, owing to the operation of some widespread influence. These facts suggest either climatic changes or regional uplifts. There is no question as to the competence of uplifts to induce dissection to proportionate depths, but climatic changes competent to bring about the incision of valleys to depths of hundreds or even several thousands of feet, as is indicated by the canyons in the ranges of Wyoming, would have to be extraordinary in magnitude. For that reason the hypothesis of changes of level seems to me the more favored one, although it should not be inferred that the other influences are excluded from participation in a minor degree.

The work of interpreting the erosion history of such a district involves largely the recognizing and discriminating of surfaces produced during successive cycles and correlating these in chronological order. Although it is often possible to recognize mature and even young topographic forms of preceding cycles of erosion, the most readily recognized features are the broad graded surfaces or flood plains which normally become wider and wider as the cycle proceeds. In Wyoming, however, a careful discrimination must be made between remnants of old river-graded surfaces, and those

other flats and terraces which are normally developed by the stripping of weak strata from harder beds in horizontal position—a process which is peculiarly effective in dry wind-swept plains. This distinction must be made particularly in the broad basins such as the Wind River and Green River basins, where the Tertiary strata have been but little disturbed. It is necessary also to bear in mind that the graded surfaces, which constitute the immediate goal of all streams, are not level, either transverse to the main stream or parallel to it. Therefore remnants of the same graded surface generally do not have the same elevation in different parts of the district, even though there has been no subsequent warping; but such remnants should bear approximately the same general relation to each other as corresponding parts of the modern floodplains bear to each other.

The studies of Westgate and Branson, already noticed, show that in the Lander district the topographic features reveal a definite sequence of cycles which may eventually be extended to a much larger region. The existing topography suggests a declining series of phases, in which the earliest cycles proceeded to old age, the intermediate ones to maturity, and the later ones only to youth. This may well be more apparent than real, however, for if any of the early stages had gone no farther than youth, the evidence of their existence would have been destroyed in those later cycles which went farther toward completion. As I am still somewhat doubtful about the correlation of the features I have seen with those described by Westgate and Branson, I present in Table II an independent scheme of glacial stages and erosion cycles, not as a final list, but necessarily as a provisional one.

Below the elevated peneplain, which has already been described as probably of Pliocene age, I find evidence suggesting at least four cycles of erosion, one of which appears to be older than the oldest glacial drift, while the rest are more or less associated with glacial phenomena. The latest cycle, which is probably complex in detail, is represented by the inner valleys with existing floodplains and their immediate terraces. It was closely associated with the last glacial stage. The phenomena of the various cycles may now be discussed more fully.

Fremont cycle: The oldest cycle recognized, of which the visible result was the "Wind River peneplain," may for the sake of uniformity be called the Fremont cycle, from the fact that the principal remnants of the Wind River plateau (Figs. 12–15) may be overlooked from Fremont Peak. In the Wind River Range the remnants of this surface attain elevations of 11,300 to over 12,000 feet, and in adjacent regions to the west other remnants supposed to be of the same age are between 10,500 and 11,000 feet above sea-level. Its features have been sufficiently described in *Jour. Geol.*, XXIII (1915), 193–94.

TABLE II

Epoch	Erosion Cycles (Largely Interglacial)	Glacial Stages	Stages according to Westgate and Branson
Recent	Post-glacial		
Pleistocene		Pinedale	Late glacial and terraces
	Lenore		
		Bull Lake	Early glacial
	Circle		Plain No. 1
		Buffalo	
	Black Rock		Plain No. 2
	Union Pass		Plains Nos. 3 and 4
Pliocene	Fremont		Summit peneplain

Union Pass cycle: The next stage in the denudation is typically represented by a post-mature surface cut upon the resistant Archean and Paleozoic rocks near the west end of the Wind River Range notably below the summit peneplain. It is evidenced by the broad, shallow, and well-graded valleys with elevations of from 9,000 to 9,500 feet at Union Pass and west of Sheep Mountain. East of Kendall, Little Flat-Top Mountain, of about the same elevation, is a beveled remnant of highly inclined Cretaceous rocks. Along the northeast slope of the Wind River Range, aged topographic forms high up on the mountain sides probably represent

this cycle, although the correlation is not assured. At the southeast end of the range, Westgate and Branson[1] distinguish two erosion cycles beneath the summit peneplain and higher than the cycle represented by Table Mountain near Lander, which I have tentatively correlated with the Blackrock cycle, farther east; these do not appear to be as distinct in the region I have studied, and were not recognized.

Still farther westward, there are, at a comparable elevation, broad, open, and well-graded valley heads both east and west of Twogwotee Pass, but always deeply intrenched farther downstream. Aged forms of similar aspect and relations have been observed between the valleys of Jack Pine and Conant creeks in the northwest part of the Teton Range. This gently sloping surface lies decidedly higher than the oldest deposits of glacial drift, but is a thousand feet or more below the tabular remnant interpreted as possibly part of the Goat Flat peneplain. In fact, the whole western slope of the Teton Range in the vicinity of the north fork of Pierre's River is a gently inclined plain rising from the general plateau level of about 6,000 feet to the bases of the more rugged peaks at 9,000–9,500 feet. Although it has been incised by deep canyons, there are still broad smooth remnants on the divides. The fact that the canyons are much deeper near their heads than farther west suggests that the surface has been tilted by being raised on the east. Although it is underlain by rocks of various types and structures, the plain is but little modified by structure.

At the west end of the Gros Ventre Range a few miles northeast of Jackson, there are rather large remnants of an ancient gentle valley slope cut across folded Paleozoic rocks. These remnants stand nearly 2,000 feet above the channels of the present streams.

No doubt the surface produced in the Union Pass cycle was broadly planed on the weak Mesozoic and Tertiary clays, although only late mature topography developed on the harder rocks near the headwaters of the streams, and some remnants of the summit peneplain were left untouched. In this cycle the latter was

[1] L. G. Westgate and E. B. Branson, "Cenozoic History of the Wind River Mountains," *Jour. Geol.*, XXI (1913), 142–59.

probably reduced very nearly to its present remnants, although its relative elevation has since been greatly increased.

Black Rock cycle: The next cycle has been named after Black Rock Meadows, near the head of one branch of Snake River, which at that point has excavated a flat-bottomed valley with gentle slopes chiefly on Mesozoic strata. Farther downstream, the flat is trenched and appears as a series of flat-topped spurs. These features lie several hundred feet lower than the valleys representing the Union Pass cycle in the vicinity. More or less generally throughout the district, the Black Rock valleys and remnants are 500–800 feet above the present stream. Along the Gros Ventre River, the cycle is probably represented by the long flat-topped spurs from one to eight miles below the mouth of Fish Creek. The surfaces of these spurs trunkate Cretaceous beds which dip from 15° to 25°, and if the intervening gulches were filled there would be a continuous graded valley floor several miles wide. On one of the remnants a thin capping of water-worn gravel is still preserved. Corresponding features may be found in the tabular areas and flat gravelly spurs which obstruct the Snake River valley below Jackson Hole at elevations of 500–600 feet above the river, and the similar forms in the lower Snake River valley near Irwin, Idaho. These forms are apparently remnants of a wider, flat-bottomed valley much shallower than the present canyon of Snake River. In the Teton Range the wide shallow valleys of similar nature, from 500 to 1,000 feet above the bottoms of the modern canyons, suggest the same cycle.

Returning eastward to the north side of the Wind River basin, we find around Black Mountain (see Fig. 24), and westward along the mountains to DuNoir River, a high plain, distinctly lower than the Union Pass cycle, and now much dissected. Most of these remnants are veneered with weathered stream-gravel which plainly indicates the origin of the plain. At the mouth of each ravine in the mountain side, an old alluvial fan is still to be seen although nearly all such fans have been dissected. In some places in this district there is evidence that there are really two plains separated by a terrace 50–100 feet high, but in general there is not sufficient basis available for resolving the Black Rock cycle into two. In the

center of the basin the tributaries have largely destroyed the plain, leaving only small mesas or isolated buttes such as Crowheart Butte.

Around Lander and the southeast end of the Wind River Range, there are mesas and shelves along the foothills cut across inclined strata, at elevations of 600–700 feet above the present streams (Figs. 30, 31, 32). These are considered by Westgate as remnants of his plain No. 2, and they also have the characteristics and relations appropriate to the Black Rock cycle as defined in preceding

FIG. 30.—Table Mountain, near Lander. A mesa cut on tilted strata and capped with gravel. (Photograph by D. D. Condit, U.S. Geological Survey.)

pages. The layer of coarse gravel 50–250 feet thick in places, forming the top of each of these remnants, has interested geologists since the time of the Hayden Survey. On account of the fact that a few of the bowlders are as much as 25 feet in diameter, and many of them 5–10 feet thick, it has been suggested that the deposit must be glacial. Westgate, however, cites the distinct although crude stratification of the material as evidence that it is stream-laid. Even larger bowlders have been carried out from the canyons of the Sierra Nevada by torrents.[1] The hypothesis that these

[1] A. C. Trowbridge, *Jour. Geol.*, XIX (1911), 706–47.

patches of gravel near Lander are remnants of torrential fans agrees with the evidence so far as I have seen it.

In the Owl Creek Range also features indicating the Black Rock cycle have been observed although but sparingly. South of Anchor certain shoulders 600–800 feet above the valley bottoms are strewn with coarse, deeply weathered gravel and bowlders, which were once water-worn. There is considerable resemblance between conditions here and near Lander. In the upper course of Green River

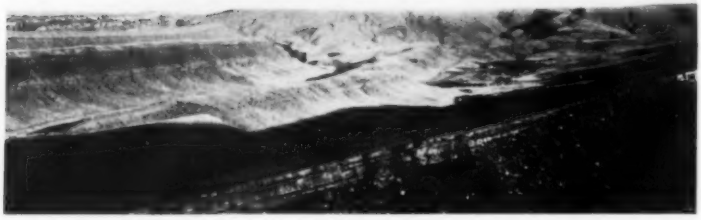


FIG. 31.—Tabular divide about twenty miles south of Lander. Probably represents the Black Rock cycle. Hogbacks of Permo-Mesozoic strata in the foreground. (Photograph by D. D. Condit, U.S. Geological Survey.)

similar high buttes and mesas, such as Flat Top Mountain near Kendall, suggest the same cycle.

In the type locality, the Buffalo old drift seems to lie always upon the remnants of Black Rock valley floors, and in the Teton Range the relations are similar. From these facts I infer that these shallow older valleys were completed about the time of the first well-recognized stage of glaciation in western Wyoming. It is a persistent and distinctive characteristic of the Black Rock surface that it is floored with thick and very coarse gravel deposits. None of the earlier or later partial plains of the region carry more than a thin veneer of such material. It has been suggested that the

coarse, stratified gravel deposits represent outwash from the ancient glaciers rather than torrential fan deposits under the influence of an epoch of desiccation. With reference to deposits now so deeply weathered, I know of no criteria that could be used to decide between these two modes of deposition. Whatever the origin, there is a suggestive resemblance between these thick coarse gravel deposits on remnants of the Black Rock plain and similar deposits in other ranges of the Rocky Mountains, such as the conglomerate

FIG. 32.—High rock-cut terrace southwest of Lander. The Carboniferous strata have been planed off at the level of Table Mountain (see Fig. 30).

of Bald Ridge on the east side of the Bighorn Range,[1] the Bishop conglomerate of southwestern Wyoming,[2] and other well-known examples.

Between the Black Rock cycle and the next one clearly discriminated there may well have been one or more cycles now represented by terraces visible here and there in the Wind River and Green River bad lands. These are, however, but little known and

[1] *U.S. Geol. Survey, Cloud Peak–Fort McKinney Folio*, No. 142.

[2] J. L. Rich, *Jour. Geol.*, XVIII (1910).

appear not to have left notable marks in any but the softest strata. For the present, therefore, they must be neglected.

Circle cycle: Benches cut across folded rocks along the sides of the mountain valleys and much wider terraces and mesas cut in the Tertiary basin are relics of a surface carved out of the Black Rock peneplain. Near the mouth of Fish Creek, the principal northern tributary of the Gros Ventre River, a broad terrace (Fig. 33) 100–200 feet above the stream is very conspicuous.[1]

FIG. 33.—Rock-cut terrace on Fish Creek, correlated with the benches at Circle. The Cretaceous strata are nearly vertical.

To the east, in the upper part of the Wind River basin, there is a prominent terrace cut on inclined strata and again standing about 150 feet above the stream (Figs. 34 and 35). A fine remnant of it stands out just east of Circle post-office on Wind River. In each case the surface is strewn with coarse, river-deposited gravel, but the layer is only a few feet in depth. As the terrace blends into the earlier moraines of the Dinwoody and Torrey glaciers, the gravels may well consist largely of the outwash deposits of the Bull Lake stage. Again, in the vicinity of Bull Lake and Fort Washakie, a nearly smooth upland surface has been planed across tilted

[1] *U.S. Geol. Survey*, Mount Leidy, Wyoming, topographic sheet.

strata at about the same height above the creek. Other remnants (Fig. 36) may be seen along the slope of the Wind River south-

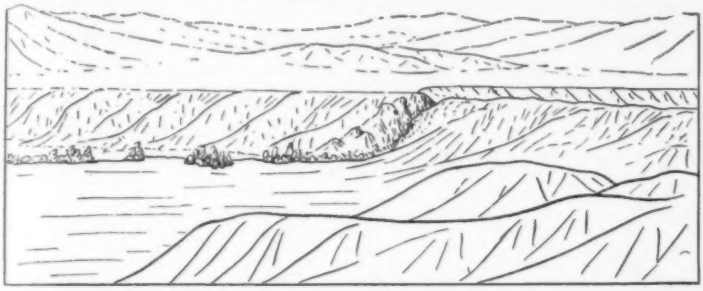


FIG. 34.—The Circle terrace near Duncan's Gorge on the North Fork of Wind River. (Drawn from a photograph.)

FIG. 35.—Rock-cut terrace of the Circle plain on Wind River at the mouth of Red Creek. Triassic (?) beds dip to the right.

west and south of Lander. This is the plain No. 1 of Westgate and Branson.[1]

[1] *Jour. Geol.*, XXI (1913), 156.

Near Anchor, on the north side of the Owl Creek Range, the most conspicuous tabular hills stand about 150 feet above the present valley bottoms (Fig. 37).

In Jackson Hole the low hills scattered about the southern end of the basin are not flat-topped, but their surfaces are only gently undulating and appear to represent late mature topography of an earlier cycle. Corresponding to the tops of these hills are wide flat-bottomed valley heads in the adjacent foothills, and all about

FIG. 36.—Mesas and terraces of the Circle cycle cut across inclined Mesozoic strata in the Shoshone Indian Reservation. The higher surface at the right may represent the Black Rock cycle.

150–400 feet above the bottom of Jackson Hole. These and similar features along the west slope of the Teton Range may correspond in age and represent the Circle cycle, although the correlation at such a distance is far from assured. Northeast of the new town of Tetonia, at the north end of the Teton basin in Idaho, there are low, nearly flat-topped mesas which have been dissected to a depth of 100–200 feet by the streams which excavated the bottom of the Teton basin. These features again are of the same order of magnitude, and have the same general relations as those typical of the Circle cycle. The Circle floodplains were once two

miles wide at the type locality, but were much broader near Fort Washakie and Lander. In the somewhat more remote headwaters of the Gros Ventre valley, the terraces are only a fraction of a mile in breadth. They are distinctly older than the latest (Pinedale) stage of glaciation. The older (Bull Lake) moraines, however, rest upon the Circle terraces and blend into them in such a way as to indicate that the terraces were parts of the floodplains in the earlier glacial stage.

FIG. 37.—Circle terraces along North Fork of Owl Creek. Bedded Tertiary volcanics in the background.

Lenore cycle: Following the last distinct rejuvenation, the inner trenches of Wind River and its tributaries were excavated in the Circle floodplains (Figs. 39, 40). Although these valleys are relatively narrow in their upper reaches, they are well graded, and the floodplains are broad enough locally to accommodate ranches, as at Lenore and Circle. They expand considerably downstream.

Farther west in the Gros Ventre valley there is a similar inner valley cut in the well-defined terrace of the Circle cycle. Fish Creek has intrenched the Circle plain to a depth of 100–150 feet, and then by meandering has developed a floodplain about 1,000 feet wide (Fig. 41). On the whole, the valleys are considerably narrower here than in the Wind River basin, but the rocks

are somewhat more resistant and the region is closer to the headwaters of the streams. Westward this inner valley merges into the floor of Jackson Hole. Since the latter is now coated with recent alluvial deposits of unknown depth, it may prove to be somewhat unlike the Wind River basin in origin. If the filling is deep it may signify local warping or faulting, and the appropriate disturbance of stream gradients; but if it is thin, as I think more probable, it may be ascribed entirely to the glacial choking of Snake River.

Inner trenches of varying width, but generally similar to those farther east, are observable along Fall or "Hoback" River, down the Grand Canyon of Snake River to its lower valley near Irwin, and also along its southern tributary, Salt River, as far up as Star valley, in Wyoming and Idaho.

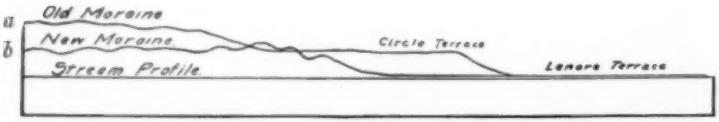


FIG. 38.—Diagram showing the relation of Circle and Lenore terraces to moraines of the (*a*) Bull Lake, and (*b*) Pinedale glacial stages. Wind River basin.

On the whole, the Lenore cycle did not go far, and resulted only in the excavation of relatively narrow valleys with slender and even interrupted floodplains, except in weak strata and along large streams. The moraines of the latest glacial stage were deposited in these valleys, showing definitely that the inner trenches were made just before the last ice advance.

It will some day be possible, through detailed local studies, to subdivide the Lenore cycle on the basis of terraces, shallow inner trenches, etc. For example, the Snake River in Jackson Hole is intrenched distinctly below the general level of the flat; at the mouth of the Grand Canyon of the Snake, the river has intrenched its gravel-strewn floodplain to a depth of 50–60 feet; and near the mouth of the Hoback River that stream has cut a trench of about the same depth through deposits of gravel into solid rock below. These features are so much more prominent in the Snake River drainage than in the Green River or Wind River basins that I am

led to think that the three systems have had somewhat different histories. Along Wind River and Owl Creek the streams are now generally intrenched 10–30 feet below the gravel-strewn terrace of the Lenore cycle, and widened according to circumstances. This has been accomplished in post-glacial time.

FIG. 39.—Crow Creek valley and Crowheart Butte, showing the broad Circle plain, beneath which the modern valley has been cut, surmounted by a monadnock carrying a remnant of an older plain. (Drawn from a photograph.)

FIG. 40.—Dry Creek valley in the Wind River basin. It illustrates the dissection, in the Lenore cycle, of the plain of Circle. The beds dip 10–15° away from the camera. The valley in the center of the view is about 150 feet deep. (Photographed by D. D. Condit, U.S. Geological Survey.)

Quaternary glaciation.—All of the mountain ranges of the district that exceed 10,000 feet in elevation bear marks left by valley glaciers of an earlier time. Indeed, a few small bodies of ice still exist in the deep cirques of the Teton, Shoshoni, and Wind River ranges. By glacial action the mountain crests have been excavated in the characteristic way, and the canyons have been modified

in varying degree. In some cases the ice descended as far as the foothills of the range, and a few of the largest ice-tongues expanded out upon the adjacent plains. It is not my purpose to map or describe in detail the glacial phenomena of each range, but rather to discuss the general nature and course of events in the district as a whole, using individual cases for illustrations and as evidence.

It is clear that the time which has elapsed since glaciers first appeared in this region has been very long, and the time since they vanished very short. On the one hand, there are deposits of till that have been so deeply eroded that only remnants of them now

FIG. 41.—The floodplain of Fish Creek in the Mount Leidy highlands. Benches on the left are remnants of the older (Circle) floodplains, cut across inclined beds.

remain, and the intervening canyons are hundreds of feet deep in solid rock. On the other hand, some of the glacial features are as fresh as if they had been made within historic times—the moraines almost untouched by erosion, the bowlders essentially unweathered, the lakes not yet filled, and the striated rock surfaces still conspicuous. In the older drift little if any trace of original glacial topography remains, and most of the surface bowlders have disappeared either through weathering or through burial by eolian dust. An examination of only one or two valleys in the district might prompt the conclusion that there were two and only two stages of

glaciation; but, after having studied the deposits of more than forty-five Pleistocene glaciers, distributed over a large part of western Wyoming, I find it no easy task to reduce the facts to such comfortable simplicity. Indeed, if disposed to support arbitrarily the hypothesis that there have been many successive advances of glaciers, I could, by selecting cases, arrange a graded series leading by almost imperceptible steps from the least modified glacial deposits which have been practically unaffected by postglacial changes, to those which have lost most of their glacial characteristics and have been eroded to isolated remnants. Before discussion of the question of successive glacial stages some general considerations need attention.

The glacial features in the several valleys differ from each other in many respects, among which the following are important: (*a*) the depth to which moraines have been intrenched by streams, and the extent to which they have been reduced in area; (*b*) the degree of preservation of distinctive glacial topography; (*c*) the closeness of relation of the moraines to modern valleys and their terraces; (*d*) the progress of weathering of glaciated rock surfaces and of the bowlders upon the moraines; (*e*) the depth of soil, particularly of loess, on the moraines.

These attributes are influenced by more or less variable conditions and one should be prepared to find drift deposits of essentially the same age, changed much in some cases and little in others. Lateral moraines resting upon soft clays may be rapidly destroyed through the growth of gullies, while moraines planted firmly on the hard Paleozoic or pre-Cambrian rocks suffer only trivial erosion in the same length of time. Drift plastered along steep slopes may be largely denuded while contemporaneous moraines lying upon interstream plateaus retain their original topography. Ponds without inlets apparently are filled much more slowly than those entered by streams, especially if those streams are eroding soft materials. Where the climate is dry, as in the Wind River basin, it is probable that the bowlders on the moraines would show fewer signs of decay than those in the moist forests on the west slope of the Teton Mountains, and also that soil and loess would accumulate more rapidly in the latter region,

because the vegetation serves to entrap the dust from the western basins.

This prelude to the general discussion of Quaternary glaciation is given in order to show that the satisfactory correlation of the different drift deposits and other glacial phenomena of the district is a difficult matter, calling for critical interpretation. In order to eliminate the effect of variable conditions, it is necessary so far as possible to compare only cases where the environment has been generally similar; and I may add that a large amount of additional information from the field is needed.

In many canyons glacial drift of two distinct ages can be recognized easily, and it seems to me there is sufficient evidence that the later stage of glaciation is divisible into two quite distinct episodes. There are a few facts which hint at a still older or fourth stage, but they may be otherwise interpreted. Without attempting an actual correlation, the three sets of deposits may be compared in general state of preservation to the late and early Wisconsin, and the Illinoian or the Kansas drift sheets in the Mississippi Valley region. In explanation of this view I shall describe the characteristics of the drift and other glacial features of the various stages here suggested, beginning with the most recent.

Pinedale stage: The youngest moraines, which for convenience may be called the Pinedale drift, are conspicuous in the vicinity of Torrey Lake and Bull Lake in the Wind River valley, Osborn ranch on Green River, Jenny Lake and Taggart Lake in Jackson Hole, around each of the large lakes near Pinedale on the southwest side of the Wind River Range, and also in many other valleys of the district. They are very rough and fresh in appearance, being covered with bowlders which themselves show but little effect of weathering (Fig. 42). Many of the bowlders of hard, fine-grained rocks show polished or scratched surfaces, even though fully exposed to the weather; and in the cirques above the moraines such surfaces, bare or now covered only with moss, are abundant. The terminal moraines are generally intact and the lateral moraines continuous, save where unusual conditions have subjected them to abnormally rapid erosion. Lakes and ponds which contain but little post-glacial filling are characteristic features of these newest

moraines, and even those lakes which lie in the courses of the main creeks have been only slightly reduced by the building of deltas or the cutting of outlets.

Bull Lake stage: The next older moraines, which I have compared with the early Wisconsin drift of Illinois, will be called the Bull Lake drift, from the locality of that name on the north slope of the Wind River Range. The deposits of this stage are definitely related to the terraces of the Circle erosion cycle in that they blend

FIG. 42.—Hills in the latest terminal moraine at the lower end of Bull Lake. The prominence of bowlders is characteristic.

into the gravel-strewn benches as modern moraines blend into their outwash deposits. The moraines are still largely intact, and by using a little imagination to supply gaps, they can be mapped in their original extent. In protected places, as on flat uplands, the topography is still visibly morainic, consisting of orderless humps and hollows. That the Bull Lake drift is nevertheless distinctly older than the Pinedale drift seems to me to be indicated by the following facts: (*a*) bowlders are by no means as abundant upon the

surface as they are on the Pinedale moraines, and those which remain show plainly the effects of weathering;[1] (*b*) lakes are rare or absent, but hollows filled with peat mark the sites of many that have

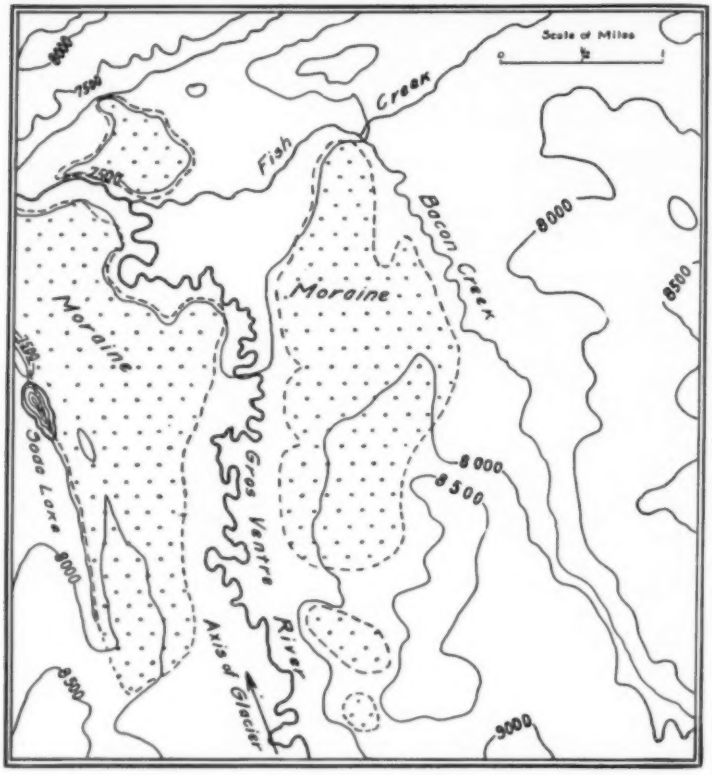


FIG. 43.—Sketch map showing the dissection of the old moraine (Bull Lake [?] stage) at the junction of Fish Creek and the Gros Ventre River.

disappeared; (*c*) the principal creeks have cut not merely sharp ravines but rather wide flat-bottomed valleys through the terminal

[1] A fact possibly related to the weathered condition of the older drift is the observed scarcity of cedar trees on the older moraines at Bull Lake, while such trees are so abundant on the adjacent new moraines that the latter appear much darker.

moraines, and the tributaries have largely dissected the lateral moraines into short pieces.

The frayed character of the terminal moraines is indicated in Figs. 43 and 44. At the mouth of the DuNoir River near the west

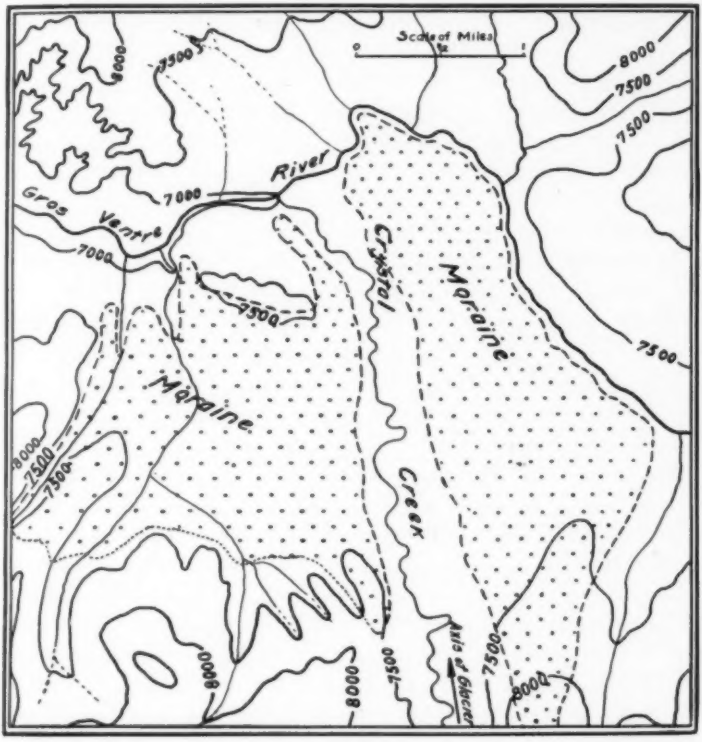


FIG. 44.—Sketch map showing the dissection of the old moraine (Bull Lake [?] stage) at the mouth of Crystal Creek, Gros Ventre Range.

end of the Wind River basin, the position of the old terminal moraine is occupied by a spacious river floodplain; nevertheless, the old lateral moraine, now 200–300 feet above the river, is still largely intact and can be readily identified by its hummocky topography. On the north side of Dell Creek, on the south side

of the Gros Ventre Range, two well-defined lateral moraines, without any terminal junction, have been beheaded upstream by the excavation of the inner valley of the modern Shoal Creek. On account of the much more rapid destruction of lateral moraines where they rest on steep slopes in soft rocks, the old lateral moraine at Sunday Peak on the Gros Ventre River has been almost completely destroyed by the development of numerous short ravines in the Cretaceous shale.

Some of the best examples of the Bull Lake moraines are to be found near the mouth of Crystal Creek (Fig. 43), and near the mouth of Fish Creek (Fig. 44) in the Mount Leidy quadrangle, along Green River south of Kendall in the Gros Ventre quadrangle, and the older moraines of Bull Lake, DuNoir River, and Dinwoody Creek in the Wind River basin. At the mouth of Teton canyon, on the west slope of the Teton Range, distinct lateral moraines have been cut into short lengths and yet they are still connected downstream by the eroded remains of a bulbous terminal moraine. On the basis of similarity of conditions these deposits are correlated with the moraines of the Bull Lake glacial stage.

The glaciers of the Bull Lake epoch were in most instances longer than those of the Pinedale epoch. Thus, on Crystal Creek the difference in length was about four miles, on the Gros Ventre River about nine miles, and on Green River apparently twenty-five miles. On the north slope of the Wind River Range, however, there seems to have been but little difference in length, and the Pinedale moraines in the valleys of Bull Lake and Dinwoody Creeks were even advanced a fraction of a mile farther than the older terminal moraines.

Buffalo stage: Certain other glacial deposits, which are evidently very much older, are readily differentiated. These may be called the Buffalo drift, from their typical occurrence along Buffalo Fork of Snake River. The deposits which appear to represent this stage now exist only in the form of remnants on flat-topped divides or isolated hills, or on spurs along valley slopes. Such surfaces have already (p. 312) been correlated as belonging to the Black Rock cycle of stream erosion. The grouping of these remnants suggests that they are parts of originally more extensive bodies

which have since been cut to pieces by the growth of canyons. The canyons have been excavated, not only through the drift sheet itself, but 200–1,000 feet in the underlying rock. Thus the deep valley of the north fork of Teton River has been cut almost entirely since the deposition of the Buffalo drift, for the river now has a V-shaped gorge devoid of glacial features in the horizontal flows of rhyolite, and the old drift caps a flat-topped divide on either side (Fig. 45). The canyon of Buffalo Fork, about fifteen miles above its junction with Snake River, is a similar trench sunk about 1,000 feet into the Cretaceous (?) shales which underlie the extensive deposits of old drift.

As should be expected, the ancient moraines have been much more extensively destroyed where they rest upon weak strata in proximity to an actively degrading stream. For example, in the

FIG. 45.—Diagram of the canyon of Teton River southeast of Ashton, Idaho, showing the present relations of the oldest (Buffalo) drift.

valley of the Gros Ventre River about seventeen miles above its mouth, there is a remnant of till identified by striated subangular bowlders exposed in a new roadway. The granitic and other distinctive rocks entering into the composition of this material indicate that the ice-tongue came originally from the Wind River Range, and probably from the canyon of Green River. Yet no trace has thus far been found of the old lateral moraines.

Uncorrelated drift deposits greatly reduced by erosion were observed on the high divide between Leigh and Teton creeks, on the west slope of the Teton Range. There the glacial origin of two or three little bodies of bowlder-clay is proven by the presence of striated stones, and other characteristics of till, but their age is not clear. One of the remnants occupies a saddle in an undulating ridge which separates two deep canyons. Another remains on the shoulder of a spur dividing the forks of a canyon 800 feet deep.

It is evident from their situations that they were deposited before the adjacent canyons were cut. It is also patent that they are but the last relics of the original moraines, of which the outlines and catchment areas can no longer be seen.

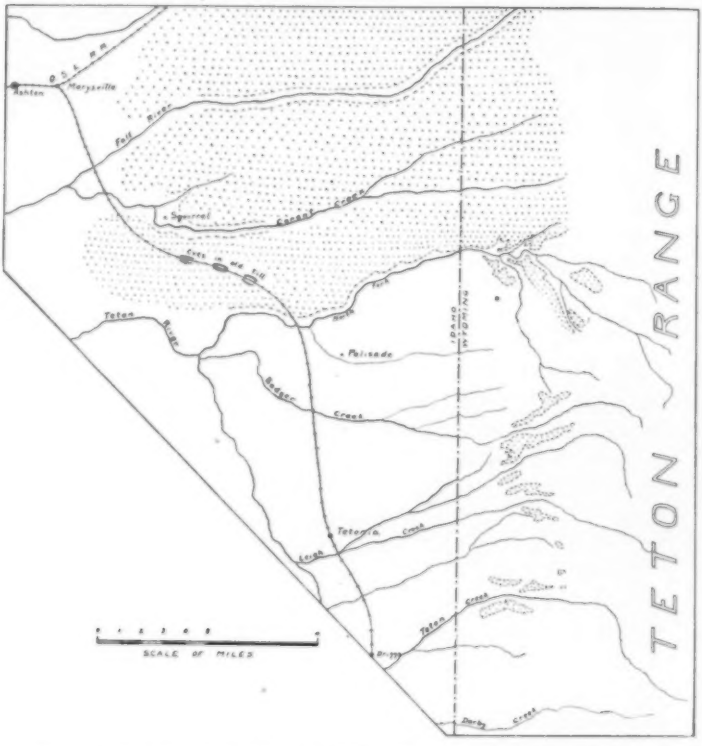


FIG. 46.—Sketch map showing distribution of remnants of old (Buffalo) drift on the northwest side of the Teton Range.

They may be regarded as drift deposited by a small glacier of the Buffalo stage from the slope between Leigh and Teton creeks, and subsequently almost destroyed by the spreading tributaries of the larger canyons. It is also possible that they may represent an earlier glaciation.

Cirques of the Buffalo stage are no longer to be identified with confidence, and it is now uncertain whether the glaciers were of the valley type or parts of an ice-cap. In most cases even the general outline of the ice-mass is uncertain. But few traces of morainic topography now remain in the drift of this age, because most parts of the region have been dissected to maturity by the growth of valley-systems. This condition is clearly shown on the broad sheet of till along the new branch of the Oregon Short Line between Marysville and the north fork of Teton River in eastern Idaho (Fig. 47). Nevertheless, on some of the broadest plateaus, where

FIG. 47.—The present topography of the ancient till sheet (Buffalo) south of Conant Creek on the northwest slope of the Teton Range.

relief is still slight, there are shallow depressions filled with peat, or still containing marshy lakes. Such features are to be found twenty miles east of Ashton, Idaho, and near the branching of Buffalo Fork of Snake River.

The surface of the old drift in the western half of the region is generally smooth and almost devoid of bowlders. This probably is due not so much to the decay of bowlders as to their burial by the eolian deposition of loess in that district to a depth of from two to five feet. Bowlders of granite on the isolated hills of sedimentary rock south and east of Kendall in the Green River valley are outside

the zone of loess deposition, and are now so much weathered that the large feldspar crystals protrude and some of them can be picked out with the fingers. The coarse, unassorted, and unstratified character of these deposits suggests that they may be glacial; and their isolated situation indicates that they have suffered greatly from erosion. They are tentatively referred to the Buffalo drift.

Glacial scratches are of course found only on bowlders of resistant rock and even then only where they have been effectually insulated from the action of the weather. Striated bowlders of Buffalo age were found in considerable numbers in the new railroad cuts, southeast of Ashton, Idaho. In that locality the old drift is more or less cemented by lime carbonate.

From these facts it seems certain that the changes which have taken place since the deposition of these bodies of till are very much greater than those which occurred between the making of the Bull Lake and Pinedale series of moraines. The conditions imply that the period between the Buffalo and the Bull Lake glacial stages was several times as long as the next succeeding interglacial interval, and many times longer than the post-glacial epoch.

Glacial drift comparable to the Buffalo moraine in its relations seems to cover most of the plateau of Yellowstone Park. Even in the seventies, as a member of the Hayden Survey, Holmes[1] recognized the fact that the deep gorge of the Yellowstone must have been cut after the deposition of the glacial drift which mantles the surrounding plateau. For some unaccountable reason, this early recognition of drift much older than the fresh moraines in the Rocky Mountain region seems to have remained unnoticed and is not mentioned even in more recent comprehensive papers on the geology of Yellowstone Park itself.

Although its full extent is no longer traceable, it is evident that the Buffalo ice covered a much larger area than the glaciers of the Bull Lake and Pinedale epoch. The latter were valley glaciers, which in but few instances pushed beyond the mouths of the canyons in which they developed. The Buffalo ice of the Teton back-slope, and probably also of Yellowstone Park, spread far

[1] W. H. Holmes, "Glacial Phenomena in the Yellowstone Park," *Am. Naturalist*, XV (1881), 203–8.

out upon plateau surfaces at least twenty-five miles from the mountains.

Summary of glaciation: From this discussion a few generalizations arise. All of the principal ranges of the district, except perhaps the Owl Creek Mountains, were glaciated during the Quaternary period. There were certainly two stages of glaciation separated by a long period of time, and the later of these can again be resolved with some confidence into two. A few facts slightly suggestive of a fourth epoch, still older than the others, are quite inconclusive. The glaciers of the Pinedale and Bull Lake stages were ordinary valley glaciers, which ran but little beyond the mountain fronts and rarely deployed outside their individual canyons. In most valleys, the younger of these glaciers were shorter than the older, although in a few instances they were not. In the Buffalo stage, however, a large piedmont glacier spread westward from the north end of the Teton Range, and Yellowstone Park appears to have been almost entirely buried under a mass of ice.

There is much resemblance between the sequence of glacial events in this district and that described by Atwood in the San Juan Mountains of Colorado. Although full confidence should not be placed in a long-distance correlation made without indulging in a more detailed and comprehensive study of the Rocky Mountains, it may be suggested that the deposits characteristic of Atwood's "Uinta," "Bighorn," and "San Juan" stages correspond in many respects to those of the Pinedale, Bull Lake, and Buffalo stages in western Wyoming. The Pinedale and "Uinta" moraines are alike in being very fresh and almost uneroded. The Bull Lake moraines resemble somewhat those of Atwood's "Bighorn" stage in being notably eroded although still traceable, but the Bull Lake moraines are rather better preserved. Like the till of Atwood's "San Juan" stage, the Buffalo moraines have been intrenched 500–1,000 feet and so reduced in area that at best their original forms can be but rudely traced, and in some places they constitute mere remnants which suggest nothing of former distribution or derivation.

Work of gravity with the aid of weathering.—Here, as in all regions of sharp relief, the steeper slopes are wasting away under the attacks of the weather; and the resulting débris has been making

its way down the slopes by rolling, slumping, and creeping. No doubt these processes have all been in operation, at varying rates, throughout the erosion history of the district. There is but little recognizable evidence of them, however, relating to topographic stages farther back than the Black Rock cycle of erosion.

FIG. 48.—Talus glacier in a cirque on the north side of Sheep Mountain, near the head of Green River.

The accumulations of talus are greatest above the timber-line, and beneath the most resistant cliff-forming strata. In the lower parts of glaciated valleys, the waste slopes have been largely swept away, except in so far as they have begun to redevelop since the ice disappeared. In a few cirques, talus glaciers, such as those described by Cross and Howe[1] in the San Juan Mountains of Colorado, have

[1] *U.S. Geol. Survey, Prof. Paper 67*, 1909.

been formed. On the northeast side of Sheep Mountain at the northwest end of the Wind River Range there is a good example showing the tongue-like form and surface corrugations (Fig. 48). Rock-falls have been observed where outcrops of the massive Bighorn dolomite have given way suddenly, perhaps because of the removal of the support previously given by the mass of glacial ice in the valley. Figs. 49 and 50 show two rock-falls of this kind in the Teton and Gros Ventre ranges. More numerous landslides of the commoner type, developing in soft or unconsolidated rocks, are observable here and there along the slopes of the canyons in the

FIG. 49.—A rock fall in Paleozoic dolomite near the head of the Gros Ventre River

district. There is a particularly large and fresh slide near the head of Dell Creek on the south side of the Gros Ventre Range. Perhaps the most novel of the many landslides in this region are the earth-flows which are especially characteristic of the Gros Ventre valley (Fig. 51). They depend upon steep slopes in soft argillaceous material such as constitutes the Jurassic, Cretaceous, and Tertiary systems. The most recent of these flows I have described in another paper,[1] and for this reason further mention of them may be omitted here.

The landslides and talus deposits are clearly of various ages. A few have been made within recent years. Many others are

[1] *Bull. Geol. Soc. Am.*, XXIII (1912), 487–92.

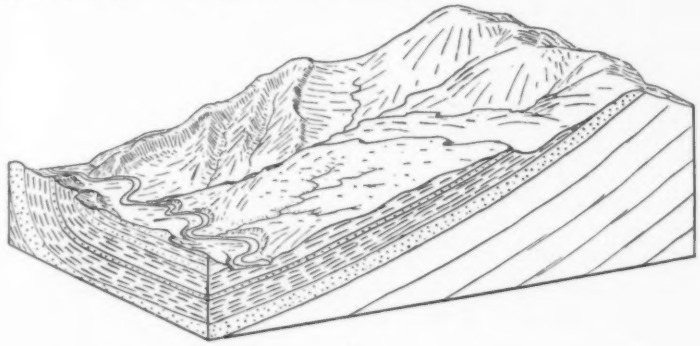
covered with forest and must be some generations or centuries old, although nearly all of their topographic features and forms are still preserved. Still others have been scarred by gullies to such a degree that they are now recognizable only upon somewhat careful examination. There are many places in which landslides of two or three distinct ages may be seen side by side on the same valley slope.

Wind work in the Quaternary period.—The climate of the entire region is moderately dry, and in the centers of the large basins it is decidedly arid. Under such circumstances the wind is admittedly

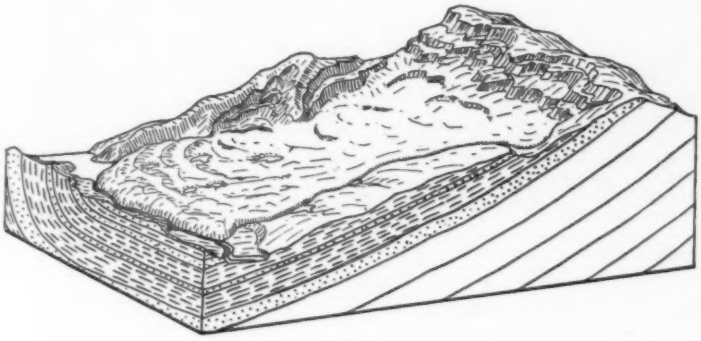
FIG. 50.—A rock-fall in the canyon of Darby Creek, Teton Range

an important agent in shaping topographic forms. The characteristics of its work are, however, greatly influenced by the varying conditions in different parts of the district. Thus, in the hot, dry central part of the Wind River and Green River basins, the erosive action of the winds can be observed daily. Bunches of sagebrush and greasewood are left perched on hillocks, where the silt has been blown out from around them by the wind. Protruding ledges of rock have been carved by the sand-blast into the usual fantastic pillars, mushroom forms, and honeycomb surfaces. Many of the smooth slopes along the sides of the valleys are swept so clean that every lamina of rock may be measured or traced for yards and even miles along the outcrop. The smooth tops of many mesas and

terraces out in the bad lands coincide with the more massive and hence resistant layers of sandstone from which the wind has completely swept off the soft beds of sandy clay.



A



B

FIG. 51.—Diagrams to illustrate the formation of an earth-flow such as the "Gros Ventre Slide" of 1909–11: (*A*) before the action began; (*B*) after the slide took place. (From *Bull. Geol. Soc. Am.*)

On the other hand, wind erosion must necessarily have wrought but slight effects upon those parts of the mountain sides that are protected by forests, and but little more upon their rocky summits. The timber belt, constituting Merriam's[1] Hudsonian and Canadian

[1] C. H. Merriam, "Life Zones and Crop Zones of the United States," *Bull. 10, U.S. Geol. Survey*, 1894.

life zones, and the sagebrush and aspen slopes of his Transition zone, are apparently, however, the sites of considerable eolian deposition. For example, along the grassy and forested western slope of the Teton Range, a thick structureless soil mantles the surface. Occasional exposures show that it is from two to twenty feet deep, entirely free from sand, gravel, or bowlders, and of a yellowish or buff color. The chemical analysis given in Table III shows that it is similar in composition to the loess of the Mississippi and Missouri valleys.

TABLE III

TABLE OF ANALYSES OF LOESS*

	1 Teton Mountains, Wyoming	2 Iowa	3 Missouri
SiO_2	72.04	72.68	74.46
Al_2O_3	12.37†	12.03	12.26
Fe_2O_3	3.38	3.53	3.25
FeO	0.37	0.96	0.12
TiO_2	.....	0.72	0.14
P_2O_5	.....	0.23	0.09
MnO	.....	0.06	0.02
CaO	1.21	1.59	1.69
MgO	1.22	1.11	1.12
Na_2O	1.83	1.68	1.43
K_2O	2.58	2.13	1.83
H_2O	3.15	2.50‡	2.70
CO_2	trace	0.39	0.49
SO_3	.....	0.51	0.06
C, organic	.....	0.09	0.12
Undetermined	1.85	.....	.....
	100.00	100.21	99.78

* Analyses 2 and 3 are taken from a paper on "The Driftless Area" by T. C. Chamberlin and R. D. Salisbury, *6th Ann. Rept., U.S. Geol. Survey*, 1885, p. 282.

† Including TiO_2, P_2O_5, MnO, etc.

‡ Contains H of organic matter. Dried at 100° C.

1. Loess overlying old drift, one mile east of Alta, Teton Creek, Teton Mountains, Wyoming. Sample taken two feet below the surface. Analyst, W. C. Wheeler, U.S. Geol. Survey, 1912.

2. Loess near Dubuque, Iowa.

3. Loess from river bluff at Kansas City, Missouri.

It is suggested that this widespread veneer of loess consists largely of the dust blown by the westerly winds from the dry regions of Oregon and Idaho and strained out by the vegetation on the mountain slopes. It is significant that such deposits are not characteristic of the Wind River and Green River basins, which

are apparently subject to the removal of dust rather than to its accumulation.

Sand dunes, which might be expected in the driest parts of the district, appear to be rare, although a few were observed along the middle course of Green River. This tends to confirm the view that in this region the dominant phase of eolian activity is erosive.

SUMMARY OF CONCLUSIONS

Divested of details and qualifications, the history of the district may now be reviewed in general terms. About the close of the Cretaceous period, the entire region was probably a monotonous plain underlain by unconsolidated sediments. Soon thereafter, tangential forces within the earth's crust produced a series of moderate folds, trending northwest and southeast. The process of folding tended to produce a series of mountain ranges and basins corresponding to the anticlines and synclines; but the uplifts were certainly being eroded even while they were growing, and after the disturbance ceased they continued to be worn down until the surface became a well-dissected mountainous or hilly region interspersed with wide, relatively flat basins.

In the Wasatch or Lower Eocene epoch, terrestrial sediments began to accumulate in the lowlands, probably in response to mild warping movements and perhaps climatic changes, which disturbed the activities of the previously graded streams. These sediments were distributed chiefly by rivers, but doubtless in part by the wind, and some seem to have lodged in lakes and playas. Sedimentation thus continued with but little interruption under a rather warm, subarid continental climate until some time after the early Oligocene. Early in this sedimentary cycle there were volcanic eruptions in the western part of the district, during which acidic lava flows and occasional beds of ash were deposited; but the much more extensive eruptions of the Absaroka Range took place later. The grassy plains of the time were occupied by ancestral horses, cloven-hoofed ungulates, rodents, gigantic titanotheres, and their appropriate carnivorous enemies.

Somewhat later, probably near the middle of the Miocene epoch, the district was notably warped and locally faulted, in part

along the structural lines established at the close of the Cretaceous, but in part at variance with them. It is probable that this mid-Tertiary disturbance involved also a general elevation which left the region above base-level, and therefore subject chiefly to erosion rather than to sedimentation.

From the mid-Tertiary revolution down to the present time, the history of western Wyoming is a chronicle of denudation. It is believed that at all times the master streams of the region controlled the general shaping of topography, although the effects of stream erosion were modified in important details by mountain glaciers, by the wind, and by slumping. The progress of general stream erosion was evidently not steady, but was interrupted by successive elevatory movements or other changes which compelled the readjustment of stream activities. In the earliest of the erosion cycles of which good evidence still remains, the region seems to have been generally reduced to a peneplain even where the rocks were tolerably resistant. This plain is believed to have been established during the Pliocene epoch.

Later cycles followed each other with more rapidity—or more probably we read the later chapters in more minute detail. They were apparently caused in large measure by general uplifts of the Rocky Mountain region, although they may well have been influenced in noteworthy degree by climatic changes, river piracy, and other modifying causes. While these erosion cycles and interruptions were in progress, there occurred certainly two, and almost surely three, distinct advances of glacial ice in the mountains, followed by as many retreats and perhaps complete disappearances. Between the glacial stages the streams continued their work and sank their valleys through the moraines and into the underlying rocks. Since the latest glacial advance only slight topographic changes have been made.

THE GEOLOGY OF CENTRAL MINAS GERAES, BRAZIL

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PART I

INTRODUCTION

GENERAL GEOLOGY
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  - Basement Complex
- Post-Archean Erosion Period
- Probable Algonkian
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INTRODUCTION

The South American continent bears resemblance to the North American continent in several respects. Like the northern continent it may be divided according to its geologic history into an eastern half and a western half. Like North America its Atlantic

side was deformed and thrown into mountains before the close of the Paleozoic. As in our own Appalachians this mountain-building period of eastern South America was followed by long-continued erosion which base-leveled the mountains. Later successive widespread uplifts produced low plateaus, out of which rejuvenated erosion has carved the present ranges. Aside from these gentle uplifts, which have occurred at several periods during later geologic history, the eastern part of the continent has exhibited comparative stability for a long time. Since the Paleozoic the deformation of South America has largely been on the Pacific side. During the Mesozoic and Tertiary remarkable stressed conditions on the Pacific border developed the great world-ridge of Cordilleras which runs from Cape Horn to Bering Strait and which makes the western portions of the two continents also geologically related.

The area considered in the present paper lies in the eastern half of the South American continent. It is that section of the state of Minas Geraes, Brazil, which lies between Diamantina (latitude 18°17′ S.) and Ouro Preto, the former capital of the state (latitude 20°23′ S.), which is situated east of the 45th meridian. In many respects this area is geologically the most typical and complex part of eastern Brazil. Running north and south across it is the Serra do Espinhaço, or Backbone Ridge of Brazil, which forms the eastern rim of the São Francisco basin and divides the waters flowing into the Rio São Francisco from those which flow directly into the Atlantic Ocean. Structurally and historically this mountain range gives the key to the geology of most of eastern Brazil, for either within the range, or closely associated with it, are all the important sedimentary formations of Minas Geraes. These comprise a great series of quartzites, schists, and iron formations with some associated limestones. East of the Serra do Espinhaço is a great area of dominantly igneous rocks, presumably Archean, which extends, with the exception of small isolated patches of overlying sedimentary rock, continuously to the sea. West of the Serra do Espinhaço is a plateau country underlain by rocks of both the sedimentary series and the basement complex.

Within this region structurally so significant, occur also the most important mineral deposits in Brazil (Fig. 1). Here is

found the gold which caused this portion of the country to be settled at an early date. Here also are found the diamonds and other precious stones for which Brazil has long been famous. And it is along the flanks of this strip of the Serra do Espinhaço that there

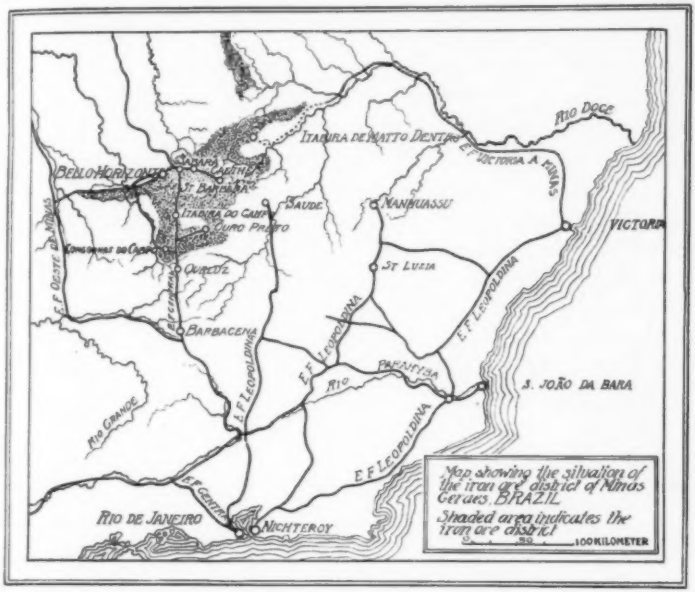

FIG. 1.—Map showing the location of the iron-ore district of Minas Geraes, Brazil

are being discovered today the still more remarkable deposits of high-grade iron ore which seem destined to develop a great industry in the future.

GENERAL GEOLOGY

GENERAL DISTRIBUTION, SUCCESSION, AND STRUCTURE OF FORMATIONS

The coastal region of Brazil throughout the states of Rio de Janeiro and Espirito Santo is composed, except for small areas of Mesozoic or Tertiary sediments occurring locally along the ocean border, of a complex of ancient crystalline rocks of which granite, gneiss, and crystalline schist are the prevailing types, and in which diorite, gabbro, and other more basic rocks occur as

intrusives. These rocks form the basement complex of eastern Brazil and are probably to be referred to the Archean. The crystalline belt extends far into the interior, at first continuously, but farther away from the coast, as patches and arms amid areas of overlying post-Archean sedimentary formations.

Eastern Brazil has been, throughout much of its geologic history, a region more subject to denudation than to sedimentation. In Minas Geraes the uncovered basement complex is now areally the most extensive surface formation. The basal granite, gneiss, and crystalline schist are nearly continuous throughout the eastern and central portions of the state. Where the younger sedimentary beds do occur, they persist in favored localities as local remnants of former widespread formations. The post-Archean sedimentary series is best represented within the limits of the Serra do Espinhaço which owes its existence and present elevation to the superior resistance of some of its quartzite beds.

The area of post-Archean sedimentary rocks of central Minas Geraes extends in a continuous belt of varying width from about latitude 20°40′ S., in south-central Minas Geraes, northwestward across the state and into the state of Bahia. Southward from latitude 20°40′ S. isolated areas of sediments continue into southern Minas. As a result of complex earth movements, the southern end of the principal sedimentary belt is wide and irregular, occupying nearly all of the area from a point about 15 kilometers southeast of Ouro Preto, northwestward to Bello Horizonte, a width of about 80 kilometers. Followed northeastward the belt narrows but continues as a strip from 5 to 20 kilometers in width almost to Diamantina, where it branches, one limb running northeastward into northeastern Minas Geraes and the other continuing northward into Bahia. Both on the east and west, this strip of sediments is bounded by extensive areas of older rocks, probably Archean, consisting of gneiss, granite, and crystalline schists. Areas of sediments, of unknown age, however, occur at various places west of the sedimentary belt, becoming more extensive toward the north.

The metamorphosed sediments, which Derby has called the Minas series,[1] are probably of Algonkian age, judging from their

[1] O. A. Derby, "The Serra do Espinhaço, Brazil," *Jour Geol.*, XIV (1906), 396.

stratigraphic position and lithology and their similarity to Algonkian sediments in other places. They lie upon the eroded surface of the basement complex, and have as their basal member a great quartzite formation. Above this quartzite, often separated from it by a thin argillaceous schist bed, is the peculiar iron-bearing quartzite known as itabirite, accompanying which are extensive iron-ore lenses. This formation is, in turn, overlain by a schist and quartzite formation of great thickness. The uppermost known member of the great series is a quartzite with associated schists. Occurring in proximity to these metamorphosed sediments, and derived from them by disintegration and decomposition, are subaerial deposits of more recent age.

Appropriate geological names taken from localities where characteristic exposures of the various formations occur have been adopted. The known succession is as follows:

Tertiary and Quaternary
- River gravels
- Tertiary clay and lignite
- Canga deposits

Mesozoic or Early Tertiary
- Diamantina conglomerate

Probable Algonkian
- Itacolumi quartzite
- Piracicaba schist and quartzite
- Itabira iron formation
- Batatal schist
- Caraça quartzite

Probable Archean
- Gneiss, granite, and schist

The various sedimentary formations are complexly distributed, occurring in some places and being absent elsewhere. Their irregularity of occurrence is due, in part, to irregularity in original deposition, but more especially to later faulting and folding followed by very extensive erosion. They are separated from the basement complex by a profound unconformity.

The most characteristic formation of the series is the Caraça quartzite which extends throughout the length and width of the sedimentary area and locally develops an extraordinary thickness.

Somewhat more limited in occurrence is the iron formation which is well developed in the broad portion of the area between Ouro Preto and Bello Horizonte, but which to the northeast and southwest becomes inconspicuous or is entirely absent. The upper formations are also local in their occurrence (Fig. 2).

The Caraça quartzite forms the most prominent mountain system of this portion of Brazil which has taken the name Serra do Espinhaço, or Backbone Range, and which divides the waters flowing westward into Rio São Francisco from those flowing eastward directly into the Atlantic Ocean. The iron formation generally forms well-marked foothills along the quartzite ridges, though locally, where well developed, and specially hard, it itself forms the main ridges while the quartzite is on the slopes. The Piracicaba schist, being soft, is inconspicuous topographically, but the Itacolumi quartzite forms a number of prominent peaks and ridges.

The distribution of formations is well shown by the topography. The mountain peaks and long continuous ridges common to this region are made up of quartzite and iron formation. They are bounded by lower areas of schist, or by an irregular undulating region of hills and valleys underlain by gneiss and granite. These sedimentary rock mountains of central Minas Geraes are, with the exception of the granite masses forming the Itatiaya Range on the southern border of the state and Caparaó Mountain on the boundary between Minas Geraes and Espirito Santo, the most conspicuous mountains in Brazil.

The characteristic deformation of the rocks of central Minas Geraes has been thrust faulting and accompanying folding. The forces in general came from the east and south, ranging between northeast, southeast, and south, forces from different directions being applied at different times, resulting in a sort of superimposition of structure. This complex structure is especially characteristic of the wide area between Ouro Preto and Bello Horizonte, where the combination of forces has resulted in the formation of a number of parallel and intersecting belts of sedimentary rock. In the southern part of this area is an east-west syncline resulting in two parallel belts of sediments; in the western part is a north-south overturned syncline causing a similar distribution, and in the

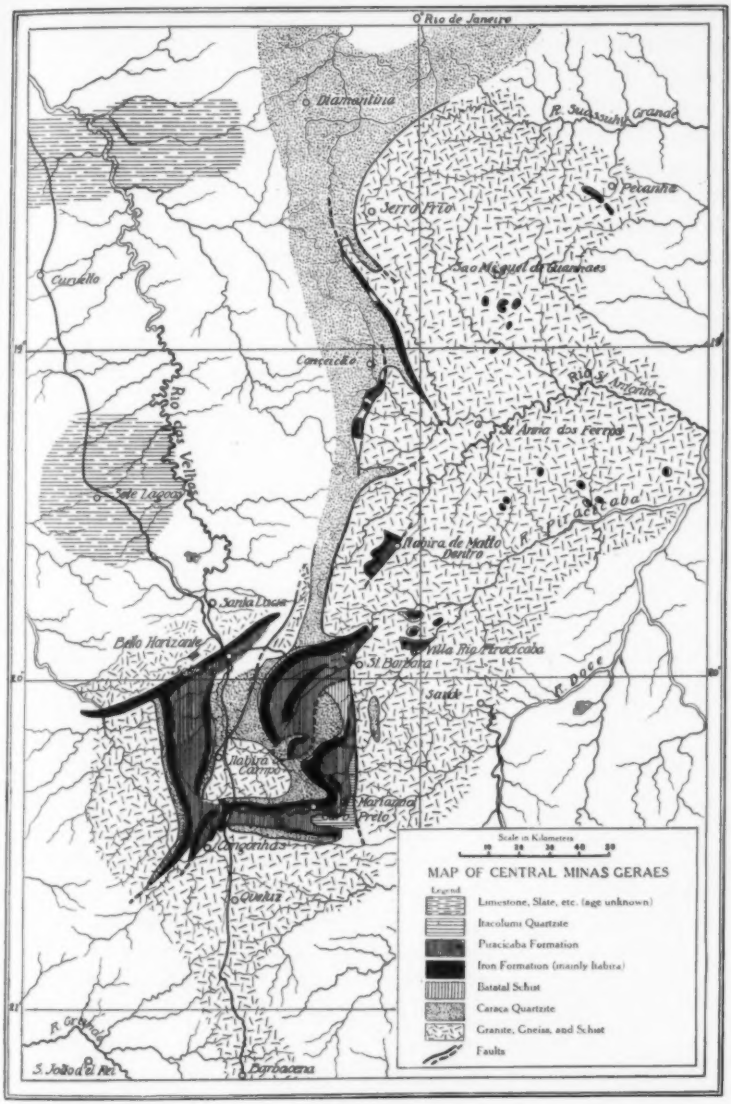

FIG. 2.—Map of central Minas Geraes

northern and eastern parts is a series of more or less parallel thrust faults, resulting in several parallel and branching belts of sediments. In the center, occupying the angle between the two synclines, is a large circular area of granite, gneiss, and schist of the basement complex raised by this combination of forces into a dome structure.

A very conspicuous result of the deformation has been the development of V-shaped branchings of the formations in various parts of the area, such as those south of Capanema, west of Cocaes, southwest of Bello Horizonte, and northwest of Serro. These V-shaped junctions can be explained by forces working in different directions at the same or at different times, in such manner that, when breaks occur in the formation, one portion of it is forced against another portion at an angle. Frequently at such junctions there has been much crushing and dislocation of the formations.

In general the irregularity of deposition, resulting in a great variation ot thickness as well as of materials, combined with the complex structural relations above mentioned, has resulted in a condition of complexity of structure and areal distribution of formations not easy to solve.

PROBABLE ARCHEAN

Basement complex.—The rocks of the basement complex consist chiefly of granite of varying composition and texture, gneiss with interlayered amphibolite, and micaceous and quartzose schists. Granite and gneiss are probably the most abundant of the rocks in the Archean areas, and of these two the granite is the more commonly observed because of its greater hardness. It forms prominent ridges in many parts of central Minas, and is commonly exposed in rounded bluffs along streams where these flow through granite areas. Crystalline schists are also abundant but are less conspicuous because, on account of the softness of these rocks, exposures are not so common. These schists resemble closely the schist beds in the Piracicaba formation and sometimes can be distinguished from them only by their general distribution. Elsewhere they may be distinguished by their more prominent recrystallization, or by the presence of pegmatite veins. Such

pegmatite veins are also abundant in the gneiss but are rarely seen in the granite. They usually consist of muscovite, orthoclase, and quartz.

The amphibolite is a banded rock occurring interlayered in the gneiss and corresponding in layering to the gneiss itself. It is a dark-green rock consisting either entirely of hornblende, or of hornblende with a small amount of feldspar. It is widely distributed throughout the region of the basement complex, and in many localities masses of considerable thickness occupy large areas. On weathering the amphibolite gives rise to a yellow ocherous soil due to the formation of abundant iron oxide. Near the surface this changes in color to a deep red which is very characteristic of the soils in many parts of the district.

Diorite and gabbro occur sparingly as later intrusions in the gneiss and schist in different parts of the district, diorite being more common than gabbro. Most of the intrusions are in the form of dikes, some of which may be traced for long distances. Some of the gabbro intrusions, however, are very limited in extent.

The relation of the three principal varieties of rock in the basement complex to each other is determined with difficulty on account of the complexity of their structure and distribution, and because of the thick covering of mantle rock which effectively conceals the greater portion of these rocks. The granite is apparently intrusive into the gneiss and schist and occurs in large irregular areas. Single masses 60 or 70 kilometers in extent are known. The granite intrusions are probably older than the gabbro and diorite. The relation between the schist and gneiss is unknown. In places the schist has been seen interlayered with the gneiss and apparently bears a relation to it similar to that which the amphibolite bears to the gneiss. If this is true the schist, gneiss, and amphibolite would seem to be the older rocks into which granite, diorite, and gabbro were intruded. Probably the gneiss and amphibolite represent respectively ancient acid and basic volcanic flows with which were interbedded quartzose and argillaceous sediments now represented by the schists. By metamorphism and deformation these were transformed into their present equivalents—

the igneous rocks to gneiss and amphibolites, the sediments to crystalline schists. The later intrusions may have taken place during, or after, the deformation.

Many areas of schist, the definite structural relations of which it has not been possible to determine, have been presumed to be part of the basement complex. During further investigations certain of these schists may be found to belong to one, or other, of the overlying sedimentary formations.

Lithologically the schists of the basement complex are extremely various. There are quartz-muscovite schists, sericite schists, talc schists, chlorite schists, amphibole schists, and argillaceous mica schists of varying texture, many of them ferruginous, others siliceous. The gneiss, on the other hand, is fairly regular in texture and composition throughout most of the district. In most localities it is medium grained with distinct banding, though elsewhere the banding is so faintly developed that it is difficult, by lithology alone, to distinguish the gneiss from later granitic intrusives. Its predominant minerals are feldspar, quartz, biotite, and hornblende.

From the foregoing descriptions it is clear that to distinguish between the various rocks of the basement complex, to separate them areally and determine their structure and relations to each other, will require much petrographic study and detailed mapping.

POST-ARCHEAN EROSION PERIOD

During the deformation and metamorphism of the gneiss, schist, and amphibolite, and their intrusion by the granite and other igneous rocks, the surface of the central Minas Geraes region was probably of a very rugged and mountainous character, and was probably elevated far above the surface of the sea. Then a period of erosion and disintegration began, for a long time the former being predominant, but later as the mountains were being worn down and acquired gentler slopes disintegration became more and more important. For a long time the products of disintegration and decomposition were largely carried away to the sea, but gradually, as the slopes became more gentle, material began to accumulate and a layer or blanket of soil formed over the solid rock. This

thickened as erosion and transportation decreased and as it thickened it became more and more thoroughly decomposed.

While there were still considerable differences of elevation the sea began to encroach upon the land, gradually occupying what is now eastern, southern, and central Minas Geraes. Apparently an arm of the sea extended westward covering the southern end of Goyaz, the southern and western part of Matto Grosso, and probably part of Bolivia. Whether the sea extended far southward into São Paulo is not known, but it is doubtful, since sediments of this age are unknown in central and southern São Paulo. To the north the sea covered northeastern Minas Geraes and a large part of Bahia, but whether it extended still farther north is not known.

It was in this sea that the probable Algonkian sediments of central Brazil were deposited. Owing to the great amount of decomposition which the rocks of the basement complex had undergone previous to the encroachment of the sea, little remained in the soil except the end products, especially kaolin, iron oxide, and silica. As the end products were derived largely from acidic granites and gneisses, silica dominated. In the shallow advancing sea the waves may be supposed to have been capable of sifting these residual materials, holding in suspension and carrying away the fine mud and iron oxide while of necessity soon depositing the coarser grains of quartz. The first material laid down upon the eroded surface of the Archean complex in the area under discussion was therefore a great mass of quartz sand. By cementation, induration, and metamorphism this has become the Caraça quartzite formation.

PROBABLE ALGONKIAN

Caraça quartzite.—The Caraça quartzite is the basal formation of the thick sedimentary series of supposed Algonkian age. Over most of the region the formation consists of more or less schistose quartzite, though it embraces a complete range from pure vitreous quartzite to quartzite schist made up almost entirely of white mica. The variations in composition and texture occur along the beds, as well as across them, so that at different places along the quartzite belts the major part of the formation may be either predominantly schistose or predominantly quartzitic. Locally the

formation may be thin-bedded, while elsewhere masses many meters in thickness and of great uniformity in texture may occur without a trace of bedding.

The distribution and structure of the quartzite are determined by the general structure of the district (Fig. 3). The dips are in general to the east or southeast at varying angles, except for minor irregularities such as occur in the region between Ouro Preto and Congonhas do Campo. Even where three or four parallel or slightly intersecting belts of quartzite occur, this regularity of

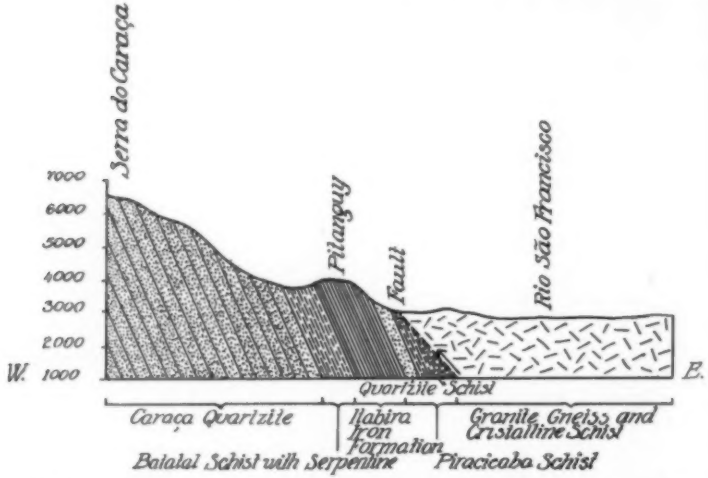

FIG. 3.—East front of the Serra do Caraça. Section through Pitanguy Hill. Elevations given in feet.

dip prevails. Such parallel belts of southeasterly dipping strata are the results of thrust faulting and overturn folding, and their regularity indicates the uniform nature of the deformation to which the region has been subjected.

The Caraça quartzite though varying in thickness extends throughout the length of the sedimentary belt, being everywhere well developed except in the region east and south of Bello Horizonte where it appears to be absent, for the iron formation lies directly on the basement complex. Along considerable portions of the

belt, especially in the northern part, it is the only one of the Algonkian formations present, being bounded on both the east and the west by rocks of the basement complex. In detail the distribution of the Caraça quartzite is as follows: Beginning at the southwest, a belt of quartzite dipping to the southeast runs northeastward to a point about northwest of Congonhas do Campo where it turns northward and continues with great uniformity to about the latitude of Bello Horizonte where it is cut off sharply by a northeast-southwest belt of sediments. To the east of it, and approximately parallel with it, is a shorter quartzite belt also dipping to the east. Between the two belts are areas of iron formation and Piracicaba schist, while to the east and west of them are granite, gneiss, and schist of the basement complex. From the structure it is presumed that these two north- and south-striking quartzite belts are on opposite limbs of an overturned syncline dipping to the east. Both belts are well shown in the topography, the western one appearing as the Serra da Boa Morte and the eastern one forming the high hills west of Itabira do Campo.

Beginning with Serra do Ouro Branco near Miguel Burnier is an east-west belt of quartzite somewhat more irregular than are the north-south belts, being broken at several places, and varying in strike in different parts, from northwest-southeast to northeast-southwest. It continues eastward to a point southeast of Ouro Preto where it is cut off by rocks of the basement complex. South of it, unconformably underlying it, are schist, gneiss, and granite of the basement complex. Some distance to the north of it and parallel to it is another quartzite belt dipping southward, being underlain and bounded on the north by granite, gneiss, and schist. Between these two quartzite bands are areas of iron formation and Piracicaba schist, so that here occurs an east-west syncline differing from the north-south syncline before mentioned in being broad and open. The southern limb forms the prominent Serra do Ouro Branco while the northern limb is not very marked topographically, being mainly composed of quartzite schist not very resistant to erosion.

The northern of these quartzite belts continues westward beyond Miguel Burnier and eastward to Ouro Preto where it

makes a sharp turn northward and then continues northwestward, thus forming a narrow eastward pitching anticline. The northern limb of the anticline dips to the northeast and rocks of the basement complex are exposed southwest of it along the axis of the anticline. At Capanema the quartzite band branches, one arm going northeastward and forming the conspicuous mountain mass of the Serra do Caraça (Fig. 4) while the other continues northwestward, forming

FIG. 4.—The Serra do Caraça at Alegria. A portion of the Backbone Range. The high Serra consists of resistant Caraça quartzite. In the middle distance are hills of the Itabira iron formation whose strata dipping toward the right reach a maximum thickness of 1,200 meters in this section. In the far distance to the right are lowlands of the granite complex.

the Serra da Capanema, then, becoming less prominent topographically, it continues northward around the headwaters of the Rio Santa Barbara.

At a point west of Cocaes the latter belt divides again, an eastern arm forming the prominent ridge above Cocaes and then disappearing, while the main belt here forms the central axis of the Serra do Espinhaço, which continues northward for many miles—a great quartzite range.

Several minor offshoots to the east occur from the northward extension of the range, and at a point west of Serro the range divides, one branch running northeastward, forming the Serra do Chifre, on the divide between Rio Doce and Rio Jequitinhonha, and the other continuing northward past Diamantina toward the state of Bahia.

The northeast-southwest belt of sediments previously mentioned as cutting off the north-south overturned syncline near Bello Horizonte consists mainly of Itabira iron formation and Piracicaba schist dipping southeast. Locally a thin layer of argillaceous and quartzitic schist, representing the Caraça quartzite, occurs at the base. The belt is of considerable extent, beginning at a point northeast of Caethé, east of the main Serra do Espinhaço, and running first southwestward past Bello Horizonte and the end of the north-south overturned syncline already mentioned, and then westward and northwestward toward Pitanguy. It forms a prominent range known as the Serra da Piedade which consists for the most part of iron formation. Toward the west, however, the quartzite becomes more prominent, forming some conspicuous mountains.

The Caraça quartzite, while present almost throughout the district, varies greatly in thickness. In the isolated sedimentary areas in the eastern part of the district, as near Villa Rio Piracicaba, there are places where it is less than 30 meters thick; in the region south and east of Bello Horizonte it appears to be in places entirely absent, while along the main Serra do Espinhaço it reaches thicknesses greater than 1,500 or 1,800 meters. The latter is the more typical development of this great formation.

The ordinary phase of the Caraça quartzite consists of quartz grains intermixed with more or less white mica. Where highly metamorphosed, and this is especially true where the formation is thin, the mica is sometimes coarsely crystalline so that individual flakes frequently reach half an inch in diameter. When quartz occurs in these phases it is also coarsely crystalline. Such coarsely crystalline phases, however, are rare. Where the formation consists largely of quartzite, it is prominent topographically, but where the schist layers are abundant and well developed, it gives way rapidly to erosion.

Both the quartzite and the schist phases are light colored, the quartzite being white, light green, or light brown according to the stage of oxidation or decomposition of its constituents. The light-brown color is due to the oxidation of ferrous iron present and is prevalent near the surface. The schists are usually white, light green, or light gray in color owing to the principal constituent, white mica.

Batatal schist.—After the deposition of a great thickness of the coarse clastic sediment which makes up the Caraça quartzite, there came a change in the character of the material being washed into the sea. The sediments became finer, whether owing to the lowering of the land surface from which the material was derived, or to a further advance of the sea upon the land. Whatever the cause, there occurred a slackening of sedimentation as well as progressive fineness. The result was the laying down of a series of varicolored clays which through metamorphism have resulted in the Batatal formation, a light-gray to dark-red, fine-grained, argillaceous schist, which overlies the Caraça quartzite conformably. This schist is perhaps best represented along the base of the Serra do Caraça, though, on account of its softness, it is seldom exposed in outcrop. Not only inconspicuous in outcrop, it is also a comparatively thin formation, seldom exceeding 30 meters in thickness. At one point, however, along the base of the Serra do Caraça northwest of the village of Cattas Altas, it suddenly thickens to more than 300 meters of schist, while at the same time the overlying iron formation gradually pinches out. The situation is somewhat peculiar and it is probable that the upper portion of the Caraça quartzite at that point is schistose, and thus is indistinguishable from the Batatal schist.

On the eastern and southeastern flank of the Serra do Caraça a sheet of serpentinized eruptive rock is found to rest upon the Batatal schist at a number of points. It is seen at Morro da Mina, and is also conspicuous in Boa Vista, near Cattas Altas, extending several kilometers northward from there till cut off by a fault. This serpentine layer always occurs at the same horizon at the top of the Batatal schist and at the base of the iron formation. It is not an intrusive, but was apparently a sheet of basic lava

spread out upon the then level surface of the Batatal sediments. The iron oxide and silica deposits which now constitute the Itabira iron formation were then laid in regular succession upon it. If this basic flow were more widely extended throughout the iron district and were of greater mass, one might be inclined to look to it for a source of the iron now locked up in the great iron formation which followed so closely upon it. Such an explanation has been advanced to explain the origin of much of the iron formation in the Lake Superior region. In their great monograph on the geology of the Lake Superior region, Van Hise and Leith have come to the conclusion that the iron formations there are so intimately asso-

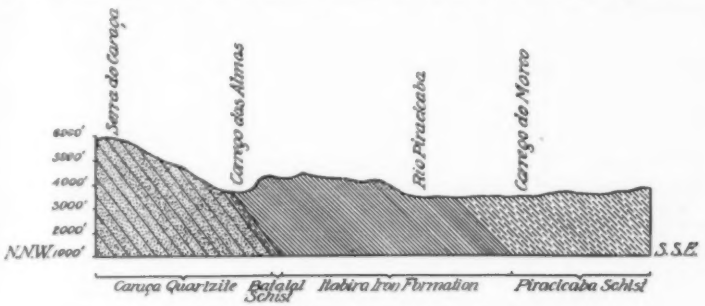

FIG. 5.—Section through Fazenda da Alegria

ciated with basic lavas that the source of the iron in the great ore beds is to be sought in the igneous activity.[1]

In Minas Geraes, however, remnants of a basic lava flow near the iron formation in the stratigraphic column have been discovered up to the present time only at the two adjacent localities just mentioned. Though these probably belong to a single flow which extended continuously from Morro da Mina nearly to Santa Barbara, this flow after all covered but a comparatively limited area which, taken together with its thinness, makes it quite insignificant in size and extent in comparison with the tremendous iron formation above it (Fig. 5). Thus it seems more reasonable to account for the deposition of the iron formation through some other agency.

[1] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *Mon. 52, U.S. Geol. Surv.* (1911), pp. 409–570.

Itabira iron formation.—The Batatal schist represents a slackening of sedimentation from the rapid deposition which characterized the laying down of the sands composing the Caraça quartzite. This slackening of clastic sedimentation continued until the close of the Batatal epoch, when very little clastic material was being washed into the sea in the region considered. The land presumably had become so low as to yield very little mechanical sediment, and with this lowering of the land surface there was probably combined a gradual retreat of the shoreline. Simultaneously with the great diminution in mechanical sediment deposited in the area under consideration, there commenced a precipitation of ferric hydroxide from solution, materials in solution being probably carried beyond the borders of the region of clastic sedimentation. This precipitation may have been due, either to purely chemical reactions taking place in the sea, or perhaps to the operation of the well-known iron bacteria which cause the deposition of ferric hydroxide from waters containing ferrous carbonate in solution. These iron bacteria are said to possess the peculiar property of utilizing as food the carbon dioxide locked up in very dilute solutions of ferrous carbonate.[1] Ferric hydroxide is left behind and is deposited as a sediment. The characteristic reaction may be written: $2FeCO_3+3H_2O+O=2Fe(OH)_3+2CO_2$. This process is operative in very dilute solutions. Apparently only two or three parts of iron per million are needed to make certain types of the iron bacteria active.

Not having much confidence in the hypothesis that the iron oxide was precipitated directly from sea-water by ordinary chemical means, we prefer to turn to the iron bacteria as perhaps forming a better working hypothesis. If such a process as this be supposed to have been steadily in operation at this time, when very little clastic sediment was being deposited, it might have resulted in the production of the extensive iron formation. For reasons which will be discussed later, this hypothesis seems to explain the

[1] S. Winogradski, "Über Eisenbakterien," *Botan. Zeitung*, Bd. 46 (1888), p. 261; Rudolf Lieske, "Beiträge zur Kenntnis der Physiologie von Spirophyllum ferrugineum Ellis, einem typischen Eisenbakterium," *Jahrb. für wissenschaftlicher Botanik*, Bd. 79 (1911), pp. 91–127.

observed facts connected with the formation of the Itabira iron beds better than any other yet suggested, and to encounter fewer serious difficulties.

Like the schist and quartzite, the Itabira iron formation is a true primary sediment.[1] It is a mixture of iron oxide and quartz sand laid down essentially as it occurs today. The principal change which it has undergone since its deposition is the dehydration which has converted the ferric hydroxide originally laid down into ferric oxide, or hematite. This dehydration, like the metamorphism of the shale into Batatal schist and the sandstone into Caraça quartzite, probably is to be associated with the intense deformation which these strata suffered during the mountain-forming movements which antedate the Devonian.

The Itabira iron formation takes its name from Itabira Peak, near the town of Itabira do Campo, a rather striking mountain of splendid specular hematite which forms a conspicuous landmark visible for many miles around. Though varying greatly in character, the Itabira formation is in general hard and resistant and much more durable than the softer schists which lie immediately above and below it. The result is that wherever the iron formation now appears at the surface in inclined beds, it stands up in prominent ridges or as a chain of "iron hills." In some places where both the iron formation and the underlying Batatal schist are very thin, the former may occur simply as a capping, or cover sheet, following the contour of ridges of Caraça quartzite. Elsewhere the iron formation constitutes a separate range of hills in front of, and parallel to, the quartzite ridge. The hills of iron formation are as a rule lower and less massive than those of quartzite, though locally, as along the western rim of the upper Santa Barbara valley, where the quartzite is relatively soft and contains a good proportion of schistose layers, the iron hills overtop the quartzites.

The iron formation varies greatly in thickness. In the ridge running east from Morro Agudo near Villa Rio Piracicaba, the whole

[1] C. K. Leith and E. C. Harder, "The Hematite Ores of Brazil and a Comparison with the Hematite Ores of Lake Superior," *Econ. Geol.*, VI (1911), 670–86; E. C. Harder, "The 'Itabirite' Iron Ores of Brazil," *ibid.*, IX (1914), 101–11.

formation ranges between 5 and 20 meters in thickness. In Morro Agudo Peak it suddenly thickens to 100 meters (Fig. 6). Thirty-odd kilometers away to the southwest, in the locality known as Alegria, on the east slope of the Serra do Caraça, it has a thickness of over 1,200 meters, which is probably its maximum. It is not a case of steady increase, or decrease, in thickness between areas some distance apart, for at the very eastern end of Alegria the iron formation is comparatively thin, and the swelling from a few

FIG. 6.—Morro Agudo, near Villa Rio Piracicaba. A peak of high-grade iron ore which owes its form to the superior resistance of the hard, specular hematite of which it is composed.

score up to 1,200 meters is accomplished in the amazingly short distance of about 3,700 meters along the strike (see Fig. 4). This very remarkable thickening of the deposit in such a short distance strongly suggests the conditions of delta deposition. If the layers of iron formation represent the foreset beds laid down, shingle fashion, on a delta front, the great total thickness of the successive layers may be readily understood, and in this way some of the grave difficulties which would otherwise be encountered in the development

of such a thick deposit are avoided. In the eastern part of the district, as along the Serra da Boa Morte, there seems to be much more uniformity in the thickness of the formation.

In chemical composition the iron formation also varies greatly, and the changes are as sudden as the variations in thickness. In some places, the entire thickness of the formation may be almost pure iron oxide containing less than 1 per cent of impurity. At other points there may have been so much arenaceous material incorporated within the iron sediments that the proportion of metallic iron is reduced to 40 per cent, or even less. But whether the percentage of iron be high or low, the impurities consist largely of rounded grains of quartz sand together with a little phosphorus, the mineralogical relations of which are not known. In places, however, the iron oxide is mixed with clay rather than sand, and beds of ferruginous schist are interlayered with sandy iron formation. Thus, while ferric hydroxide was being precipitated, a certain amount of sandy sediment, and locally, also, clay were washed in to mingle with the precipitate. The presence of impure limestone beds in the lower part of the iron formation, as southeast of Bello Horizonte, shows that carbonate precipitation locally accompanied the iron-oxide precipitation. In some portions of the formation, the sand is more or less evenly disseminated, while in others it occurs more often as distinct sandy partings, or laminae, which separate thin beds of relatively pure iron oxide. The temporary inwash of clastic sediment in the form of sandy partings probably marks unusual storms, or stormy periods, during which more of the terrigenous material found its way beyond the borders of general clastic sedimentation. The rock breaks more readily along the planes of these sandy partings than elsewhere, and hence possesses a somewhat sandy fracture face, so that it appears to contain more sand than is actually the case.

The purer portions of the iron formation, where the proportion of metallic iron exceeds 50 per cent, are regarded as iron ore, while the more sandy portions of the formation are designated itabirite. Formerly the term itabirite was applied as a formation name to the entire iron formation member of the sedimentary series, and included the iron ore as well as the sandy portions and schistose

layers. But now its use is being restricted, and the name is applied only in a petrographic sense to the peculiar iron-oxide bearing quartzite which constitutes the sandy portion of the iron formation.[1] There is, however, a complete gradation between the itabirite and the ore.

Piracicaba formation.—After a period of very little wash from the land, during which the iron formation was laid down through rapid precipitation chiefly, an epoch of more abundant clastic sedimentation again set in. This change was probably brought about by a gentle uplifting of the land relative to the sea-level. At first only the finer muds were laid down in the region under consideration; later, with changing conditions, there were oscillations both in the direction of diminishing clastic sedimentation and a return to the iron-oxide and calcium-carbonate forming conditions, and also in the direction of increasingly coarse clastic sedimentation with the deposition of what has since become quartzite. Under these fluctuating conditions which followed the deposition of the Itabira iron formation there was laid down a great mass of sediment, in which clays and muds predominated, but within which there were included quite extensive lenses and more or less irregular beds of quartz sand, iron oxide, and also calcium-carbonate deposits. Through subsequent metamorphism these sediments were altered to argillaceous and quartzite schist, quartzite, iron formation, and limestone. The name Piracicaba formation has been given to this series from the Piracicaba River, whose upper course near Santa Rita Durão and in Alegria follows the strike of these beds.

The lenses and beds of limestone and iron formation occur principally in the lower part of the Piracicaba formation, being interlayered with schists, while the quartzite beds predominate in the upper part. Limestone lenses, though usually small, are numerous in many parts of the district, especially in the central and southwestern parts. The limestone is generally impure, containing, besides calcium carbonate, carbonates of magnesium, iron,

[1] The term itabirite is coming into more general usage as is shown by the fact that it has been applied to iron-oxide bearing quartzites occurring in certain parts of Europe. See F. Beyschlag, J. H. L. Vogt, P. Krusch, *Ore Deposits*, I, 113, 194 (translation by S. J. Truscott).

and manganese. Different lenses differ in composition, some being reddish or purplish in color and containing manganese carbonate as the principal impurity, while others are grayish or brownish and contain iron carbonate as impurity. In places thin layers of itabirite occur in the limestone lenses, or considerable thicknesses of interlayered limestone and itabirite may occur.

The iron formation lenses in the Piracicaba formation are generally more extensive than the limestone lenses but are more local in their distribution. In lithology they are similar to the Itabira iron formation, consisting mainly of itabirite but containing also lenses of pure hematite and beds of ferruginous schist. In most cases the iron formation lenses stand up as ridges above the inclosing schist.

The schists making up the lower part of the Piracicaba formation are mainly argillaceous, gray, red, or purple in color. In the upper part sericitic, talcose, and quartzose schists are more common.

Next to the Caraça quartzite the Piracicaba formation is probably the most widespread of the metamorphosed sedimentary rocks. It is almost coextensive with the former, except in the northern part of the district where it is absent in many places on account of faulting, but on the other hand it is present in places where the Caraça quartzite is absent, as in the region southeast of Bello Horizonte.

Like the other sedimentary rocks, the Piracicaba formation is of variable thickness. Furthermore it is not always easy to draw the division line between this formation and the overlying Itacolumi quartzite, since beds of quartzite become increasingly prominent, in the upper portion of the Piracicaba formation. And as the Itacolumi quartzite is represented only at a comparatively few points in the district, the full thickness of the Piracicaba formation is to be observed only in a limited number of places. But judging from the exposures where the entire formation is present, it would seem to be seldom less than 300 meters in thickness and generally many times this. It is a great mass of sediment, of sufficient bulk to lay a heavy tax upon nearly any system of dynamics and method of sedimentation which may be supposed to have resulted in this thick pile of beds.

Itacolumi quartzite.—The series of indurated rock formations is capped, so far as the iron-ore district is concerned, by a thick quartzite which is not very different lithologically from the Caraça quartzite. As this upper formation is perhaps displayed to best advantage in the prominent peak of Itacolumi, the popular lookout point near Ouro Preto, it may well take its name from that well-known mountain. It is the youngest member of the regular sedimentary series yet discovered in central Minas.

While this formation where best exposed is predominantly quartzite, it contains also a large proportion of schistose rocks. The quartzite grades laterally into sericite, quartz, and talc schists, so that, in places, the formation is largely composed of schist with a few prominent and persistent layers of quartzite. This variation in lithology is so characteristic both of the Piracicaba formation and of the Itacolumi quartzite that the two may perhaps well be regarded as one formation, being formed during a continuous period of deposition, schists predominating in the lower part and quartzite in the upper part. They strongly suggest delta deposition, individual layers being seen to grade from coarse quartzite into argillaceous schist within a distance of 4 or 5 kilometers.

In fact, there is much to indicate delta deposition in most of the members of the Minas series. The Caraça quartzite, Itabira iron formation, Piracicaba formation, and Itacolumi quartzite all exhibit rapid lithological variations as their layers are traced along the strike as well as across it. At the same time, they show also in some places great thicknesses and extremely rapid variations in thickness. These are not the results to expect if the sediments were laid down in regular succession upon the relatively flat and uniform ocean floor; but they are just what might be anticipated if they represent the topset, foreset, and bottom-set beds of delta formation. Under the former hypothesis it is not easy to see how such great thicknesses of shallow water deposits could be formed under any rational system of crustal dynamics; under the hypothesis of inclined sedimentation the total thickness of the series of shingling layers laid down in shallow water may very easily become as great as the strata of the Minas series require.

The name Itacolumi is an old one in geological literature and has been variously applied by different writers. As far back as 1822 Eschwege proposed the name itacolumite for a quartzose talco-micaceous rock which he found abundant in, and characteristic of, the gold and diamond fields of the Serra do Espinhaço.[1] Eschwege himself recognized that the rocks to which he gave the name itacolumite were not a unit, and in consequence noted two groups, one schistose and the other massive, but he lumped together under the general name of itacolumite all the quartzose rocks of the region, which has been an incubus on Brazilian geological studies.[2]

For a long time these rocks were generally regarded as belonging to the primitive igneous crust of the earth,[3] but later geologists have shown them to be clearly metamorphosed sediments. By the more recent writers (Derby, Gorceix) the two divisions of the original itacolumite have been considered to be independent formations.[4]

While the term itacolumite has been variously applied to the quartzites and quartz schists of the Serra do Espinhaço, it also has been used as a petrographical term to designate the peculiar flexible sandstone, or quartzite, which is an oddity found at several points in the district.[5] But this property of flexibility is characteristic of only an insignificant portion of the whole formation.[6] If the term be retained for the future, its only proper place would seem to be as the petrographic name for this flexible phase of the quartzite, for there seems to be little reason for applying a single mineralogical or petrological term to such a great and varied succession of metamorphosed sedimentary formations as are now found to make up the Backbone Range.

[1] Wilhelm von Eschwege, cited by O. A. Derby, "On the Accessory Elements of Itacolumite, and the Secondary Enlargement of Tourmaline," *Am. Jour. Sci.*, V (1898), pp. 187–92.

[2] O. A. Derby, "The Serra do Espinhaço, Brazil," *Jour. Geol.*, XIV (1906), footnote, pp. 374–75.

[3] A. de Lapparent, *Traite de Geologie*, 2d ed., 1885, p. 654.

[4] O. A. Derby, *Am. Jour. Sci.*, V (1898), 187.

[5] E. S. Dana, *Textbook of Mineralogy*, p. 190.

[6] O. A. Derby, "On the Flexibility of Itacolumite," *Am. Jour. Sci.*, 3d ser., XXVIII (1884), 203–5.

Itacolumite as a formation name has been used, not only for the quartzite above the iron formation (the quartzite out of which the peak of Itacolumi has been carved), but also for the great quartzite series (Caraça quartzite) which, throughout the district, underlies the iron formation. That the quartzite which makes up the peak of Itacolumi is distinct from the tremendous quartzite formation of the Serra do Caraça is a fact which does not seem to have been brought out clearly by those who have studied this region; nor has it been clearly recognized that the quartzite which forms such a large part of the Serra do Espinhaço from Ouro Preto northward to Diamantina is the lower. But these two quartzite formations are quite distinct and are separated from one another by the Itabira iron formation and two schist series. If the name of Itacolumi be applied to one of the quartzite formations, it would seem fitting that it should be applied to that one which occurs in the peak of Itacolumi. This is the upper quartzite.

In areal extent the Itacolumi quartzite is much more limited than the Caraça quartzite. This is chiefly the result of erosion which has swept away the upper members of the Minas series from many localities where the lower members still remain. The Itacolumi formation is nowhere better displayed than just south of the city of Ouro Preto in the mountain ridge which culminates in the peak of Itacolumi, where there are perhaps 1,200–1,500 meters of quartzite exposed. The upper quartzite appears again on the north limb of the Ouro Preto anticline, as a conspicuous ridge just north of the village of Bento Rodrigues.

Whether the Itacolumi quartzite was once overlain by younger sediments of the same general series, or not, is uncertain. As yet, no evidence of a younger member of the series has been recognized. But as the Itacolumi quartzite, though a resistant formation, remains only at a few points in the whole district, it is not impossible that younger, and less resistant, beds may once have capped it and since been removed by erosion.

Summary.—This whole great series of sedimentary formations is apparently conformable throughout. Above the base of the Caraça quartzite no unconformity of any moment has been noted. But from top to bottom, not a single fossil has been found within

the series which might aid in determining its geologic horizon. The strata have been metamorphosed to such an extent that fossil forms might originally have been present in these beds and have since been obliterated in the process of metamorphism. But to what extent the absence of fossils is due to an original paucity of impressions in the original sediments, and to what extent to obliteration of existing forms by subsequent metamorphism we cannot say. The age of the series therefore remains problematic. It is simply known to rest unconformably upon the probable Archean complex. The general nature of the strata harmonizes well with the hypothesis that these beds are of pre-Cambrian age. This is the age generally assigned to the series by the geologists of the Brazilian Survey. At the present time we can hardly go farther than to note the general parallelism between this Brazilian metamorphic series and the Proterozoic sediments of other parts of the world, especially the Lake Superior Algonkian series. The heavy quartzites, schists, and iron formations indicate not very widely different conditions in these two regions. But while the sedimentary series in Minas presents a strange parallelism to the Algonkian series of the Lake Superior region in North America, and to various other pre-Cambrian terranes, no definite evidence has yet been found to preclude its belonging in whole, or in part, to the early Paleozoic.[1]

PRE-DEVONIAN DEFORMATION

Just when this long period of sedimentation in central Minas was interrupted is not yet apparent. What is known is that it was followed, whether shortly, or after a considerable interval, by a period of great deformation. Mountain-making movements profoundly affected a belt running across central Minas.[2] The strata were both folded and thrust-faulted on an extensive scale. At the same time the rocks suffered metamorphic changes; the sandstones became quartzites, the shales were altered to the present schists, the carbonate rocks were recrystallized, and the iron formation dehydrated to the hematite and itabirite which we see today.

[1] See J. C. Branner, *Geologia Elementar*, Rio de Janeiro, 1906, p. 217.

[2] O. A. Derby, "The Serro do Espinhaço, Brazil," *Jour. Geol.*, XIV (1906), 347–401.

The rocks did not everywhere yield to the stresses in the same way. In the southeastern part of the district the strata were thrown into open folds, though these folds show less symmetry than those of the Jura or the Appalachian system. With the folding there is also some faulting associated. But in the northeastern portion of the district very little folding has occurred. That region has suffered, instead, very extensive thrust faulting which repeats the sedimentary series, and by thus repeating the outcrops of iron formation becomes a factor of much economic importance. The fractures have occurred along lines trending for the most part northeast and southwest, or parallel to the Atlantic coast. The faults are overthrusts from the southeast and east.

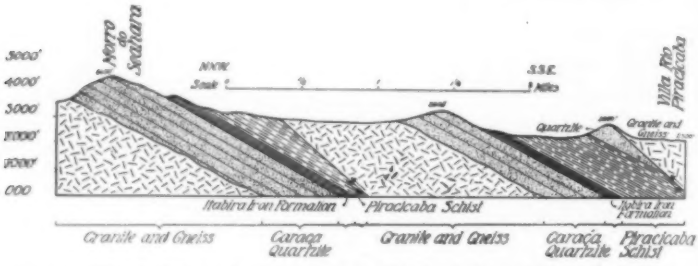

FIG. 7.—Slice-faulted section between Villa Rio Piracicaba and Morro do Seahara

The type of faulting can perhaps best be described as slice faulting (Fig. 7). The strata, instead of yielding to the stresses by wrinkling and folding, were sliced off in a succession of inclined blocks nearly all dipping toward the east or southeast, and the crustal shortening accomplished by movements between the inclined slices. In the northern portion of the Minas Geraes iron-ore district, the slice faulting has caused an alternation of the crystalline complex with the sedimentary series. Nearly everywhere the basement complex is the surface formation on the upthrust side. On account of the great erosion which the region has suffered since the period of deformation, the sedimentary formations have persisted only on the downthrown side of each fault. In the western part of the district also, faulting would seem to dominate folding.

Some of these fault lines are apparently of great length. A great fault forms the eastern front of the Serra do Espinhaço, or Backbone Ridge, at Cocaes and from there runs northward for many miles. Then, as we go farther north, there appear in front of it to the east successively new faults arranged *en échelon*. Each of these, in turn, commences a new front range slightly to the east of the previous range. The old ranges continue northward as successive ridges behind the front. This system of faulted ranges runs northward into the state of Bahia.[1] The displacement along the major fault planes cannot be determined, inasmuch as the sedimentary formations have completely disappeared from the upthrust side, so that the crystalline complex alone remains. It is probably great. In the minor slice faults the displacement in some cases is as low as 300 meters. In general the faulting in central Minas Geraes shows a marked similarity to that in the Appalachian region of the United States and that in the Canadian Rockies of Alberta.

These deformative movements were very general, apparently involving most of the Atlantic border of Brazil south of Cape St. Roque, and possibly also Uruguay and portions of the province of Buenos Aires in Argentina. The mountains formed at this time would seem, in a way, to be the Atlantic counterpart of the Andean ranges on the Pacific border. South America was squeezed from the Atlantic first and from the Pacific later.

How closely the period of deformation followed the sedimentation is as yet unknown. Minas Geraes affords little evidence, but in several of the neighboring states, Matto Grosso, São Paulo, and Parana, strata of Devonian age, but slightly disturbed, are found resting unconformably upon the wrinkled strata which participated in these orographic movements.[2] The mountain-building movements were therefore accomplished before the Devonian. That the deformation did not immediately precede the Devonian is evident from the amount of erosion suffered by the mountains

[1] O. A. Derby, *op. cit.*

[2] J. E. Branner, *Geologia Elementar*, pp. 230–31; O. A. Derby, "Geologia da região diamantifera da Provincia do Parana, no Brazil," *Archivos do Museu Naçional de Rio de Janeiro*, III (1878), 89–96.

before the incursion of the early Devonian sea. In São Paulo and Parana, the basal beds of the Devonian (which have been assigned to Lower Devonian) rest unconformably on a westward dipping, now slightly warped surface of these old deformed rocks in such a manner as to show that the sea crept in over a region of little or no relief.[1] An interval of much erosion is therefore implied.

The location and trend of these mountain ranges is worthy of note for their bearing upon the major problem of earth movements and deformation. It is no new fact that the ranges of eastern Brazil are rather strikingly parallel to the border of the continent, and not far back from the coast. In Minas Geraes the repeated overthrust faulting has nearly all come from the southeast. The strata of the faulted slices nearly always dip toward the Atlantic. The picture of the Atlantic Ocean segment crowding the eastern side of the South American continent, squeezing it and forcing it upward like a triangular wedge and wrinkling and slicing the edge comes very appealingly to mind. At a later time the Pacific Ocean segment seems to have done the same on that side.

PALEOZOIC—EARLY MESOZOIC EROSION PERIOD

After the great period of mountain-building we have evidence only of a long period of erosion whose final result was to develop an approximate base-level which is, at present, only preserved on the crest of the Serra do Espinhaço. The amount of material removed from the upthrust blocks was great, suggesting that the interval between the end of the deformation and the completion of the base-level was a long one. The process of base-leveling was probably not rapid, since the hard Caraça quartzite is a very resistant formation and would have been reduced slowly. That the process progressed nearly to completion is evidenced by the character of the crest of the Serra do Caraça which, even today, preserves in places a well-developed plain (Fig. 8). The Serra do Caraça being composed of more resistant rock than the surround ng region, this quartzite area would be the last portion of the region to be brought to base-level. As the upturned Caraça strata were

[1] J. B. Woodworth, "Geological Expedition to Brazil and Chile, 1908–9," *Bull. Mus. of Compar. Zool. Harvard College*, LVI, 42.

truncated, it is safe to assume that all the rest of the region was close to base-level.

MESOZOIC—EARLY TERTIARY DEPOSITION

Diamantina conglomerate.—On the truncated, even crest of the Serra do Espinhaço, high-level gravels, now cemented into a conglomerate, are found at various points along the range, particularly

FIG. 8.—Peneplained crest of the Serra do Caraça, near Alegria. The inclined quartzite strata have been trunkated and the old erosion surface still persists over extensive areas on the top of the Backbone Range.

in the vicinity of Diamantina. The top of the Backbone Range in that region is very broad, partaking perhaps rather more of the nature of a narrow plateau belt than of a mountain range. The broad open tracts of comparatively level upland are so distinctive as to have been termed *chapadas* (table-lands) by the natives. While considerably dissected by subsequent erosion, the broad open country upon the top of the Backbone Range is the modified surface of the old peneplain (Fig. 9). At various points on these *chapadas*, or upland plains, especially in hollows or former river

channels in the old surface, are found deposits of residual clay and gravel, more or less imperfectly cemented. This material is all thoroughly weathered and of a residual nature. The pebbles in the conglomerate are mostly of quartzite, but with a sprinkling of pebbles of iron formation, schist, quartz, basic igneous rock, and diamonds. With the conglomerate is associated a considerable amount of sand and of clean white to pinkish clay, mostly kaolin, with some bauxite. This material for the most part represents

FIG. 9.—A *chapada*, or table-land, forming the summit of the Backbone Range near Diamantina. The diamond-bearing conglomerates are accumulations of residual gravels collected in depressions or old stream channels on the peneplained surface.

the final products of the rock weathering, and its presence perched upon the smooth crest of the Serra do Espinhaço above the rest of the region would suggest that it is to be connected with the base-level stage in the history of the region. This is the celebrated diamond-bearing conglomerate which has brought fame and wealth to the district, and which would be interpreted in physiographic studies as the high-level gravels which mark the peneplain stage. Subsequently, during later erosion cycles, some of the conglomerate

material has been washed down on to lower benches and terraces along the courses of some of the streams which dissect the plateau, and today diamond mining operations are also carried on at these lower levels.

LATER EROSION AND DEPOSITION PERIODS

General uplift.—As to the age of the peneplain nothing definite is known, but it would seem most likely to belong to the late Mesozoic or early Tertiary. At some time subsequent to the formation of the plain, the region was uplifted as a whole with but little change in the attitude of the strata. Rejuvenated erosion then commenced to carve the present mountains out of the uplifted plateau. The resistant quartzites remained as ridges, while the softer schists and readily disintegrated granites and gneisses were more rapidly worn down and removed. In this tropical country the granites and gneisses appear to be the least durable of the formations, owing to the rapidity with which they crumble to pieces following the weathering of their ferromagnesian constituents. The micas, amphiboles, and pyroxenes are readily attacked by humic acids and by the carbon dioxide of the atmosphere. Weathering of these constituents allows the crystalline mass to crumble into arkose which is removed by the streams. The result is that in Minas Geraes the areas of granite, because of the feeble resistance of this kind of rock to the accelerated chemical action characteristic of weathering in the tropics, have become the lowlands. Some prominent granite ridges occur, but on examination it is generally found that they are composed of light-colored granite in which the ferromagnesian constituents play a subordinate part. The quartzite formations in general owe their resistance to erosion mainly to the fact that they contain a very small percentage of readily decomposable minerals.

Tertiary canga plains.—The erosive processes which have carved the mountains of central Minas Geraes from the uplifted peneplain did not go on uninterruptedly. There were times of checked erosion, locally at least, followed by rejuvenation. These lesser cycles are shown by various local plains and remnants of plains in different parts of the region. One of the most notable of these is

the high-level canga plain in the locality known as Gandarella, 40 kilometers northwest of Ouro Preto.

Canga (from Itapanhoacanga, a village in central Minas) is a peculiar ferruginous conglomerate consisting chiefly of fragments of iron formation cemented with a nearly pure iron-oxide cement. It is formed by a surface disintegration of the iron formation which consists largely in the removal of silica, and solution and redeposition of iron oxide. In some places the canga has been deposited almost *in situ*, while elsewhere it has been transported for considerable distances and deposited, either on areas of iron formation, or on adjacent areas of other rocks.

Such canga deposits have probably been forming ever since the iron-formation beds were exposed to surface erosion, and are being abundantly formed at the present time. As a consequence they are found at many different elevations. A long period of quiescence, like that in which the land was worn low following the pre-Devonian deformation, was therefore probably accompanied by abundant canga deposition which formed extensive canga plains on, and adjacent to, the belts of iron formation. But subsequent erosion has been so extensive that today few remnants of canga formed during the great base-leveling period remain.

The Gandarella canga plateau, already mentioned, is the most conspicuous of the high-level canga plains and is situated on the summit of the divide separating the waters of the upper Santa Barbara valley from those of the upper valley of the Rio das Velhas. This canga plateau has an approximate elevation of 1,450 meters, a little lower than the Serra do Caraça. Whether it is to be regarded as a portion of the Caraça peneplain, now at a lower level than the rest of the plain, and so more or less contemporaneous with the Diamantina conglomerate, or whether it is to be taken as the work of a later cycle of erosion, and to be correlated with evidences of planation at a similar elevation in Alegria and near Antonio Pereira, may perhaps best be left open for the present. Deep valleys have been cut in this remnant of the canga plateau along both sides of the divide. Along the bottom of one or two of these at Gandarella, there occur irregular deposits of clay and sand containing lignite and fossil leaves. On the basis of the plant

remains, these deposits have been referred to the middle or late Tertiary—probably Miocene or Pliocene.[1] They are distinctly younger than the canga plateau which is therefore certainly older than the Pliocene, and probably older than the Miocene.

Similar deposits of Miocene or Pliocene clay, sand, and lignite occur near the village of Fonseca,[2] east of an extensive canga plain of later age, which occurs along the eastern front of the Serra do

FIG. 10.—A plain of canga formation, between Santa Rita Durão and Agua Quente.

Caraça. This younger plain is very conspicuous over the areas of softer formations east of the Serra do Caraça. The canga plain abutting the east foot of the Serra do Caraça between the village of Agua Quente and Santa Rita Durão (Fig. 10) is a particularly well-preserved portion of it. The softer schists, gneisses, and granites east of the present Serra do Caraça had, with the exception of some of the more resistant lenses in the iron formation, been

[1] H. Gorceix, "Bacias terciarias de agua doce nos arredores de Ouro Preto," *Ann. da Escola de Minas de Ouro Preto*, III, 95–114; Rio de Janeiro, 1884; Joaquim Candido da Costa Sena, *Ann. da Escola de Minas*, N. 10 (1908), p. 17.

[2] H. Gorceix, *op. cit.*

reduced to a common level. Upon this plain, material washed down from the iron-formation monadnocks developed a covering sheet of canga. The canga formation, by obliterating some of the remaining irregularities in the erosion surface, has produced a remarkably level plain, much of which still remains. This canga plain is now at an average altitude of about 900 meters above the sea. Judging from the occurrences at Fonseca it appears to be of later age than the lignite deposits, which have been referred to the Miocene or Pliocene, and would seem to belong to the late Tertiary. Over considerable areas it has scarcely been trenched at all.

Conglomerate formations.—Benches, and other remnants, corresponding to the canga plains in the neighborhood ot the iron formation, are also to be seen in the Diamantina region. These remnants occur in the neighborhood of the streams which have worked back and partially dissected the plateau-like Backbone Range. As the formation of the range is quartzite, the gravels developed on these plains are quartzose, though possibly to be correlated with the iron-formation conglomerate, or canga, of the iron-ore district. As these gravels and conglomerates are composed of concentrated residual material derived from diamond-bearing formations, they have been extensively worked for diamonds.

PRESENT STATUS OF EROSION

The formation of these several Tertiary plains was terminated supposedly by uplifts which accelerated stream action and started their dissection. Portions of the canga plain near Agua Quente have suffered considerable erosion since its formation. Toward the northeast, in the region between the Serra do Caraça and the Piracicaba iron-ore district, the plain has been much carved. This area being for the most part farther from the hills of iron formation, the thick capping of tough canga which has preserved the plain intact at Santa Rita Durão and Agua Quente was much less developed. As a result, erosion progressed more readily. The easily weathered underlying granites and gneisses which almost exclusively make up this region have been cut into a state of mature erosion, though the level of the former peneplain is well preserved in the tops of these low hills.

As no attempt was made to correlate erosion cycles in the different parts of the district, little can be said of these upward movements of the land surface. One such uplift of the plateau-forming type which affected the coastal region of Brazil in this latitude was that which has given rise to the Serra do Mar, or Coast Range. The effects of this movement were undoubtedly felt by the drainage systems farther inland in Minas Geraes. The Serra do Mar presents a very abrupt face toward the sea. At many points it is really a plateau scarp which has the appearance of a mountain range when viewed from the coast. Judging from the abruptness of this plateau scarp, the upward movement which produced it must have occurred late in the Tertiary, or possibly even early in the Pleistocene.

Present topography.—The present topography of central Minas Geraes has resulted, to a very large extent, from differential erosion of rock formations which offer varying resistance to the processes of degradation. The mountains and ridges, valleys and plains, have been carved out of a region which has been folded and faulted and afterward reduced to base-level. The location of the present topographic features has been determined by the underlying rock structure. Wherever, because of faulting or folding, the heavy quartzite formations appeared at the surface of the plain out of which the present topography was sculptured, they resisted erosion far more than the other rocks, and now remain as mountain ridges. The iron formation, at most points somewhat less resistant than the quartzite, but throughout most of its extent more lasting than adjacent schists, stands up as a chain of foothills in approximately parallel arrangement to the higher quartzite ridges. The schists, by yielding more readily to erosion, have developed comparative lowlands in the midst of which isolated ridges appear wherever a lens of quartzite, or hard iron formation, occurs.

But the conspicuously weak formation is the basement complex. The granites and gneisses are especially susceptible to the chemical disintegration which is induced by the tropical conditions. Their ferromagnesian constituents are so readily attacked by the carbon dioxide of the atmosphere and the humic acids from the rank vegetation, aided by the hot, humid climate, that the rock rapidly

crumbles to pieces and the crystalline areas become lowlands. But on account of comparatively recent uplifts, the granite areas of central Minas Geraes are not yet reduced to plain conditions, though they represent a state of advanced erosion. The hills are mostly small and very numerous. They produce the peculiar knobby, hummocky topography which characterizes so many areas of crys-

FIG. 11.—View toward the Serra do Caraça from the Morro do Seahara showing the topography resulting from the unequal resistance of the formations; quartzite ranges in the foreground and in the distance; Morro Agudo, a pyramidal peak of iron ore, to the left of the center of the picture, and the billowy lowlands of granite beyond.

talline rock within the tropics, and which has been aptly likened by Eschwege to the billows of a rolling sea (Fig. 11). Wherever erosion has become sluggish in these lowland areas, the rapid disintegration of the crystalline rock has formed a very thick covering of mantle rock which effectively conceals the solid rock from view.

Reviews

An Introduction to the Geology of New South Wales. By C. A. Süssmilch. Sydney: Angus & Robertson Ltd., 1914. Pp. 269, figs. 92, tables 6, with folding colored map.

The present volume is a revision and enlargement of the first edition which appeared in 1911 and which was then welcomed as treating in a concise and judicious manner the more important features of the geology of New South Wales. After devoting one chapter to physiography, detailed historical geology is taken up, period by period. One of the most commendable features of the treatment, and one which will be especially appreciated by geologists from other countries, is the summary at the close of each chapter in which the essential and significant features of the period are given in their proper relations. From this the reader gets the correlations and conclusions of the author in a most convenient and serviceable form for use.

In New South Wales, orogenic movements are recorded in the pre-Cambrian and Paleozoic eras only. The most important of these movements appear to have taken place at the close of the pre-Cambrian, at the close of the Ordovician, at the close of the Devonian, and, in the northeastern portion of the state, also at the close of the Carboniferous and of the Permo-Carboniferous periods. But it is worthy of note that throughout the Mesozoic and Cenozoic eras, the crustal movements, not only of New South Wales, but also of Australia as a whole, appear to have been almost entirely of the epeirogenic type.

Bearing upon the existence of the hypothetical Gondwana land, in the opinion of the reviewer, is Süssmilch's statement that from New South Wales, in common with the rest of Australia, the extraordinary group of terrestrial and flying reptiles which dominated the Mesozoic land life of Europe and North America is conspicuously absent, the only vertebrates known to have lived during this era being fish, amphibia, and a few marine reptiles. If Australia had been connected by land with Asia, and especially with South Africa, where terrestrial vertebrates were so remarkably deployed and developed early in the Mesozoic, these animals should have invaded Australia also. The higher terrestrial reptiles seem to have been as completely cut off from Australia during the Mesozoic era as were the placental mammals in the Cenozoic.

R. T. C.

Oklahoma Geological Survey Bulletin 22. Part I, "Director's Biennial Report"; Part II, "Mineral Resources of Oklahoma and Statistics of Production from 1901 to 1914." By C. W. SHANNON.

Bulletin 13. Volcanic Dust in Oklahoma. By FRANK BUTTRAM.

The great progress in the development of the mineral resources in the state of Oklahoma in the last ten years is made clear by the following statistics:

VALUE OF MINERAL PRODUCTS OF OKLAHOMA

	1903	1913
Coal	$6,386,463	$8,542,748
Petroleum	142,402	59,581,948
Natural gas	1,000	7,436,389
Asphalt	28,150	91,416
Granite	9,030	30,678
Sandstone	6,500	1,010
Limestone	56,140	246,912
Lime	4,800	12,160
Cement	.....	1,258,676
Gypsum	234,621	330,416
Clay products	534,977	573,371
Sand and gravel	.....	39,457
Lead	.....	548,064
Zinc	.....	1,306,368
Salt	2,070	259
Mineral water	.....	26,231
Other products	.....	5,527
Total	$7,406,153	$80,031,630

The report is accompanied by maps showing the distribution of the mineral resources in the state, as well as a map showing its physiographic divisions.

Volcanic dust has been found at widely separated localities in the state. In one place it has a thickness of 9 feet. The dust rests upon formations as young as Pliocene, and is believed to have come from sources 600 miles or more away. R. D. S.

"A Contribution to the Optical Study of the Amphiboles." By W. E. FORD. *Am. Jour. Sci.*, XXXVII, 179–93, figs. 11.

A study with a view to correlating the optical properties of analyzed specimens with their chemical composition. Extinction angles were found

to be nearly identical in specimens of notably different composition. In general the extinction angle seems to decrease with increasing iron, but the author points out that the composition may vary in a complex way and no very sure conclusions can be drawn.

A. D. B.

Ninth Report of the Director of the Science Division. By JOHN M. CLARKE. New York State Museum Bull. 164. 1913. Pp. 241, pls. 46.

This publication includes the 66th Report of the State Museum, the 32d Report of the State Geologist, and the Report of the State Paleontologist for 1912. Although unaccompanied by descriptions, there are 36 plates illustrating the Devonian fossils of Brazil and of the Falkland Islands. A full description of the fauna is to be published by the director of the Geological Service of Brazil.

The object in printing these plates is to show the distinctive characters of the southern Devonian fauna. Although fundamentally related, it is apparent that the genera of the northern and southern American habitats developed in separate basins with restricted communication. From the fossils there is indication of a continuous strand line from South America through the Falkland Islands to South Africa.

T. T. Q.

Stratigraphy and Paleontology of the Alexandrian Series in Illinois and Missouri. Part I. By T. E. SAVAGE. Extract from Bull. 23, Illinois State Geol. Survey. 1913. Pp. 124, pls. 7.

This part of the subject treats only the Girardeau and Edgewood limestones. Part II on the Essex and the Sexton limestones is in preparation. The report discusses the stratigraphic and paleontological relations of the series. A large part is a description of the fossils.

Alexandrian series is the name proposed for the early Silurian strata of Illinois and eastern Missouri which occupy a position above the top of the generally accepted Richmond and below the Brassfield (Ohio Clinton) limestone. The series consists of a number of closely related formations; these record a succession of oscillatory northward sea advances separated by breaks in sedimentation due to temporary withdrawals of the sea. The Girardeau was the earliest and the least extensive invasion; the cycle closed with the most widespread, the Sexton Creek submergence.

T. T. Q.

Geological Report on Arenac County. By W. M. GREGORY. Michigan Geol. and Biol. Surv. Publ. 11, Geol. Series 8. 1911. Pp. 148, pls. 6, figs. 18, map 1.

The county is underlain by Mississippian and Pennsylvanian formations which dip slightly to the south. The economic resources are very slight. Limestone, gypsum, and clay are of local usefulness.

T. T. Q.

Annotated Bibliography of Iowa Geology and Mining. By CHARLES KEYES. Iowa Geol. Surv., Vol. XXII. 1913. Pp. 908.

Most of the first 150 pages of the bibliography are given to historical material. The bibliography is arranged alphabetically under the names of authors and subjects.

T. T. Q.

Prince George's County. By WILLIAM BULLOCK CLARK. Maryland Geol. Surv. 1911. Pp. 251, pls. 13, figs. 3. Accompanied by *Prince George's County Atlas*, 2 maps.

The sixth of a series of reports dealing with the physical features of the several counties of Maryland. A full discussion of the stratigraphic geology of the county accompanies a description of the physiography, mineral resources, soils, forests, climate, and hydrography.

The geologic formations represented in the county range from Archean to very recent. After the Archean, no formations are represented below the Potomac group of the Comanchean. Later formations represent the Cretaceous, the Eocene (Pamunkey), the Miocene (Chesapeake), and later periods.

T. T. Q.

The Manhattan Schist of Southeastern New York State and Its Associated Igneous Rocks. By CHARLES REINHARD FETTKE. A dissertation (Columbia). Annals N.Y. Acad. Sci., XXIII, April 30, 1914, pp. 193–260, Plates VIII–XV.

The erosion of northeast-southwest trending anticlines and synclines has exposed the Manhattan schist in a series of roughly parallel belts south of the Highlands of the Hudson and east of the Hudson River. The Manhattan is a quartz-mica-feldspar schist and the young-

est bedrock formation of the region. It is believed to be a greatly metamorphosed series of "argillaceous and sandy shales, argillaceous sandstones, and arkoses which represent a thickness of several thousand feet." The associated igneous rocks are, in the order of decreasing age, basic sheets and flows, granitic intrusives (batholiths with radiating dikes of granite and pegmatite), basic intrusives, and granite and pegmatite intrusives, a basic dike. The Manhattan schist apparently overlies the Inwood limestone conformably. The Inwood-Manhattan series is thought by Merrill, Dana, Mather, and others to be equivalent to the Cambro-Ordovician Poughquag-Wappinger-Hudson River series; it is believed by Berkey to be pre-Cambrian.

V. O. T.

The Constitution of the Natural Silicates. By F. W. CLARKE. U.S. Geol. Surv. Bull. No. 588. Pp. 128.

In the opening chapter the author outlines some of the bases upon which structural formulae may lie, but in the remainder of the bulletin the structures are worked out by simply matching valences in such a way as to agree with the empirical formulae. Until our methods of synthesis are better worked out, and the decomposition of silicates is better understood, it is difficult to justify the speculative structures advanced, as they do not rest on a foundation of experimental study, but rather on the more mathematical concept of valence and chemical combination.

A. D. B.

Our Mineral Reserves. By G. O. SMITH. U.S. Geol. Surv. Bull. No. 599. Pp. 48.

In response to a demand for information as to sources of various mineral products the director of the Geological Survey has prepared this bulletin, which deals with the general situation, and briefly summarizes the condition of the industries producing some twenty-odd products.

A. D. B.

The Darwin Silver-Lead Mining District, California. By ADOLPH KNOPF. U.S. Geol. Surv. Bull. No. 580-A, pp. 1–18. Figs. 3.

Some of the ore bodies in this region are of contact metamorphic origin, and some are transitional; but most are fissure veins. For the most part, the ore bodies are found in the "lime-silicate" rocks which are metamorphosed sedimentary rocks. The deposits are of interest in that they show the transition between contact metamorphic deposits and fissure veins.

A. D. B.

Notes on the Unaweep Copper District, Colorado. By B. S. BUTLER. U.S. Geol. Surv. Bull. No. 580-B, pp. 19–23.

Notes of a two-day reconnaissance. The ores occur in fissures cutting both igneous and sedimentary rocks. The district is practically idle, and has never advanced beyond the prospecting stage.

A. D. B.

Some Cerusite Deposits in Custer County, Colorado. By J. FRED HUNTER. U.S. Geol. Surv. Bull. No. 580-C, pp. 24–37. Figs. 5.

Describes the deposits of cerusite 12 miles northeast of Silver Cliff. The ores are in a crushed fault zone. The mines have been idle for more than ten years. The two days spent in the field by the author preclude the possibility of any exact statements regarding either the general geology or the ore deposits.

A. D. B.

The Grand Gulch Mining Region, Mohave County, Arizona. By JAMES M. HILL. U.S. Geol. Surv. Bull. No. 580-D, pp. 38–58. Figs. 10.

"The ore bodies occur around the sides of a plug-like mass of rock, which is sedimentary in origin but is entirely unlike the rocks that enclose it." The ore bodies, carrying copper, are more or less lens-shaped replacements of the rocks in which they are found. The author shows interesting drawings of the relation existing between chalcopyrite, bornite chaleocite, and malachite, as successive steps in the alteration of the primary sulphide.

A. D. B.